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PERFORMANCE EVALUATION OF THE SATURN INSTRUMENT UNIT ENVIRONMENTAL CONTROL SYSTEM SUBLIMATOR UNDER SIMULATED FLIGHT CONDITIONS

T. L. Ridings and R. E. Southerlan

ARO, Inc.

February 1967

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NOTICES

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FOREWORD

The work reported herein was done at the request of the National Aeronautical and Space Administration, Marshall Space Flight Center, Huntsville, Alabama, under System 921E.

The results of tests presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The tests were conducted from December 7, 1965, to July 15, 1966, under ARO Project Nos. SR1608 and SR1621, and the manuscript was submitted for publication on October 26, 1966.

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This technical report has been reviewed and is approved.

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ABSTRACT

Twelve refrigeration units (sublimators) were subjected to simulated flight environments and evaluated as to their critical starting characteristics and heat-transfer capacity under nominal operating conditions. The sublimator is used to cool various instrument components aboard the Saturn S4B stage of the Saturn IB and Saturn V vehicles. It is a two-component system using pure water (which is sublimated through porous sintered nickel plates) as the coolant and a methanol/water (M/W) solution (which comes into thermal contact with the plates) as the heat-transfer fluid to cool the instrument packages. Various M/W inlet temperatures (heat load), and water inlet pressures, were imposed on each sublimator, and its critical starting limitations were defined. Heat-transfer capacity was determined by conventional calorimeter methods for each set of conditions. Starting characteristics for each sublimator were adequate and satisfactory. All sublimators except one performed at or above the rated 9-kw cooling capacity at nominal conditions. In addition to the 12 units evaluated under simulated flight conditions, one unit was subjected to certain developmental tests for the purpose of determining the effect of low heat load on the sublimator.

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I. ILLUSTRATIONS

SECTION I
INTRODUCTION

The operating temperature of the instruments in the Saturn IB and Saturn V Instrument Unit (IU) is controlled by a liquid-coupled, cross flow heat exchanger system designated as the Environmental Control System (ECS) (Figs. 1 and 2, Appendix I). The instruments are mounted on "cold plates," (Fig. 3) through which is circulated a 60-percent methanol, 40-percent water (by weight) solution. Heat is absorbed by this solution and carried to one of two heat exchangers (see Fig. 4). Before lift-off, a pre-flight heat exchanger provides refrigeration via a ground support system. A few seconds before lift-off, the pre-flight heat exchanger is separated from its ground supported refrigeration system, and no cooling of the methanol/water (M/W) solution takes place during the first 1-1/2 min after launch. When the vehicle reaches the required altitude, the in-flight heat exchanger or sublimator is activated and provides the necessary refrigeration for the duration of the mission.

As its name implies, the sublimator operates on the principle of sublimation. Heat is transferred from the closed-cycle M/W solution (hot fluid) and used as the heat of sublimation in the state change of ice (cold fluid) to water vapor in the open cycle side of the heat exchanger.

The sublimator, especially for missions of a few hours duration, has several advantages over other types of refrigeration units because of simplicity of operation, compactness, and light weight. A typical sublimator, type ECS, can provide 9 kw of refrigeration for 8 hr (up to 20 kw for shorter lengths of time), weigh less than 400 lb, and occupy less than 10 ft^3. One electrical input is required to open a water supply solneoid valve, the only moving part of the refrigeration system. The cooling process is continuous for the duration of the water supply and is self regulating, thereby conserving the water supply, only using what is required for the actual cooling.

Three basic objectives were pursued in this test program: (1) Determine the operating pressure of the IU, (2) determine performance characteristics and operating limits of each sublimator, and (3) evaluate under simulated flight trajectory conditions the reliability of each sublimator and the associated support systems.

Since the sublimator is vented to the inside of the IU stage, it was necessary to determine if the operating pressure in the IU at altitude would be sufficiently low to support the sublimation process. The

sublimator will not operate properly at pressures above that of the triple point of water (4. 6 mm Hg). Therefore the pressure in the sublimator exhaust vent region must be held below this maximum pressure. The IU internal pressure should be at least twice as low as the pressure in the sublimator vents so that choked flow will exist there. Besides the sublimed vapor load exhausting from the sublimator into the IU, there is also a significant gas load (mostly GN_2) from various systems in the IU. Therefore a sufficient vent area from the IU to the space external to the vehicle is required.

The primary method used to accomplish the second objective was the definition of the critical starting conditions curve. This curve is the boundary between a safe operating zone and a breakthrough (BT) zone. A breakthrough is the result of liquid-phase water carrying over through the porous plates and into the exhaust vents as seen in Fig. 5. Breakthrough is brought on by the existance of either or both of the following conditions: (1) Excessive heat load (evidenced by M/W inlet temperature) or (2) excessive water pressure differential across the porous plates (evidenced by the water inlet pressure).

The critical starting conditions curve was defined by making test runs at various heat load and water pressure conditions and plotting these in terms of their results, i. e., good start (GS) or breakthrough. A general set of points which define this operating boundary is shown in Fig. 6.

The final objective of this test program was to evaluate, under simulated flight trajectory conditions, the reliability of each sublimator and the associated support systems. This "flight profile" run was the last test run made on the particular sublimator before its return to NASA. This test consisted of a simulated flight trajectory pressure (Fig. 7) versus time profile of the GN_2 pressurization system and the activation of the sublimator at the programmed time of flight with the predicted heat load conditions imposed on the sublimator. Refrigeration capacity was measured, and observations were made as to the manner in which the sublimator started and ran during the various stages of its operation.

SECTION II
THERMODYNAMIC ANALYSIS

Under design operating conditions, the M/W solution (60-percent methanol, 40-percent water, by weight) flows through the sublimator at a rate of 7800 lb_m/hr with an inlet temperature of 63.7°F and an

outlet temperature of 59.0°F. This cooling process requires heat transfer from the M/W at a rate of 30,000 Btu/hr (9 kw) and an optimum water consumption of 29.7 lb_m/hr. A mission of 7.5 hr requires 223 lb_m of water. Consider the steady-state open system of two fluids shown in Fig. 8.

2.1 HOT FLUID (M/W)

Heat loss can be calculated for a unit mass of fluid using the general energy equation reduced to the conditions of steady flow and neglecting kinetic and potential energy changes. Therefore,

$$q = h_{out} - h_{in} = \Delta h \tag{1}$$

where q = heat transfer from M/W, Btu/lb_m

h = enthalpy of the M/W, Btu/lb_m

The specific heat, C_p, is defined by

$$C_p = \left(\frac{\partial h}{\partial t}\right)_p \approx \left(\frac{\Delta h}{\Delta t}\right)_p$$

or

$$\Delta h = C_p \Delta t = C_p(T_2 - T_1) \tag{2}$$

Substituting Eq. (2) into Eq. (1)

$$q = C_p (T_2 - T_1)$$

or

$$Q_h = \dot{M}_h \, C_p \, (T_2 - T_1) \tag{3}$$

Where Q_h = hot fluid (M/W) heat-transfer rate, Btu/hr

$\dot{M}_h$ = M/W mass flow rate, lb_m/hr

C_p = M/W specific heat, Btu/lb_m-°F

T_1 = M/W inlet temperature, °F

T_2 = M/W outlet temperature, °F

2.2 COLD FLUID (WATER)

Heat gain for the cold fluid can also be calculated from Eq. (1), obtaining the enthalpy values from the steam tables. There are two changes of state on the water side of the sublimator. The liquid water

freezes in the porous plates when exposed to the vacuum conditions present in the vehicle, and the solid ice then sublimes to vapor as a result of heat input from M/W. The diagrams of temperature-entropy for water and the cross section of a sublimator module as seen in Fig. 9 show the various processes occurring in the sublimator. Numbered locations on the temperature-entropy diagram correspond with those on the module cross section.

At 1 water enters the two water channels of each module at 70°F and 5 psia. At 1 and 2 water seeps through the porous plates and is exposed to low pressure. Evaporation occurs at the low pressure water surfaces because of pressure imbalance with the necessary heat of vaporization obtained from the water. Thus, the water temperature is lowered until ice plugs form in the pores of the porous plates, and a pressure equilibrium is attained at the solid-vapor interface within the porous plate 2.

At 2 and 3 the subliming solid-vapor surfaces in the porous plates receive the heat of sublimation from M/W which is transferred across the water channels. The resulting vapor is then vented through the sublimator exhaust to the vacuum of space surrounding the vehicle.

Since enthalpy is a thermodynamic property, only the end points (1 and 3) need be considered for water heat gain calculations. The following end point conditions have been assumed for all water calculations.

$$\text{Enthalpy of the water, } h_f = 38.04 \text{ Btu/lb}_m$$

$$\text{Enthalpy of the steam, } h_g = 1070.60 \text{ Btu/lb}_m$$

$$\Delta h = 1032.56 \text{ Btu/lb}_m$$

Therefore,

$$q = \Delta h = 1032.56$$

or

$$Q_c = 1032.56 \ \dot{M}_c \tag{4}$$

where

Q_c = heat-transfer rate of cold fluid (water), Btu/hr

$\dot{M}_c$ = mass flow rate of cold fluid (water), lb_m/hr

Environmental heat transfer to the system is negligible. Therefore, the M/W heat-transfer rate should be equal to (but opposite in sign) the water heat-transfer rate,

or

$$\dot{M}_h \ C_p \ (T_2 - T_1) = -1032.56 \ \dot{M}_c \tag{5}$$

For sample calculations, see Appendix III.

SECTION III
APPARATUS

3.1 TEST CHAMBER

Test environments were provided by the Aerospace Research Chamber, ARC (12V), a stainless steel space simulation chamber 12 ft in diameter and 14 ft in height (Fig. 10). A liquid-nitrogen-cooled shroud completely lines the inside of the chamber providing a 77°K heat sink and a cryopump for 77°K condensables. Primary chamber pumping consists of a 750-cfm roughing pump, 32-in. oil diffusion pump, a Roots-Connersville blower, and 140-cfm mechanical forepump combination. In addition, there are 120 ft^2 of 20°K cryosurface cooled by a 1-kw gaseous helium refrigerator. Performance of the chamber pumping system used in this test is shown in Fig. 11.

3.2 INSTRUMENT UNIT SIMULATION BOX

An intermediate enclosure (see Fig. 10) was required for testing the sublimators. This was necessary in order to simulate the pressure environment of the IU caused by component outgassing and by the sublimator steam exhaust. Vent ports were located symmetrically around the IU simulation box. The IU simulation box volume versus vent area ratio was scaled to the actual Saturn dimensions.

3.3 ENVIRONMENTAL CONTROL SYSTEM

3.3.1 Sublimator

The sublimator is a compact finned-core heat exchanger of a modular design (Fig. 2). Each module contains a finned M/W channel enclosed by two finned water channels. The outer wall of each of the enclosing water channels is a porous sintered metal plate which vents to a steam exhaust zone, which is exposed to the vacuum conditions present in or about the vehicle.

Water flows into and fills the water channels, seeps through the porous plates, and at some point inside the porous plate is exposed to a pressure below that of the triple point and freezes.

The "hot fluid," M/W solution flows through the center channel of each sublimator module in parallel fashion at an average temperature of approximately 62°F at nominal flight conditions. Heat is transferred

across the enclosing water channels to the ice plugs in the porous plates, thus supplying their subliming solid-vapor surfaces with the latent heat of sublimation. The resulting vapor is vented overboard, and the subliming ice is replenished by the water accumulator system. Two sublimator designs, differing only in the direction of the exhaust, were tested under simulated flight conditions of pressure, heat load, and operating temperature. The original design sublimator exhausts directly through the mounting panel port in the skin of the vehicle. The modified sublimator is designed to exhaust into the IU and then in turn through symmetrically located ports in the vehicle skin, thereby eliminating any unbalanced thrust components that might have occurred with the original design. Operationally, both types function in the same manner.

3.3.2 Water Supply System

Two different water supply systems were used in this test program. During the early part of the test program, water supply located external to the test chamber was used. This system consisted of a closed water tank on scales so that the amount of water used during each test run could be determined. A positive control of water pressure to the sublimator was provided by a mechanical vacuum pump, a GN_2 storage bottle and regulator, and appropriate gage system manifolded to the water tank. The other water supply system was one of the type that will be used aboard the Saturn IU. This bladder-type flight accumulator was mounted in the IU simulation box alongside the test sublimator (see Fig. 12). The weight of water required to fill the accumulator was recorded each day so that the output of the water flowmeter could be checked. Two methods of GN_2 pressurization were used with the flight accumulator during this test program. The method used during the majority of test runs (Fig. 13) consisted of a GN_2 line running directly to the bladder of the flight accumulator from a pressure tank outside the chamber. The pressure in this tank was controlled in the same manner as was used with the external water supply tank described above. The other pressurization method used was referred to as the flight profile method (Fig. 14) and consisted of a GN_2 supply of 16 psia located outside the chamber leading to an orifice regulator which was part of the flight ECS. This orifice regulator is located just beneath the flight accumulator and serves a dual purpose. First, during the ascent trajectory of the vehicle, before the activation of the sublimator this orifice regulator vents the bladder of the accumulator. At a predetermined time, when the proper altitude is attained, the sublimator is activated (i. e., the water valve is opened), and flow is initiated from the accumulator. The orifice regulator is designed to maintain 5 psia on the bladder by directing from the 16-psia supply only the amount of

GN_2 required. That which is not required bypasses the bladder via a vacuum bleedoff line and vents to the vehicle environment.

3.3.3 M/W Circulating System

The closed loop M/W system is shown in Fig. 13. A 1600-lb solution of 60-percent methanol, 40-percent water (by weight) contained in one of two storage tanks located external to the test chamber was circulated by a centrifugal pump through the sublimator at the rate of 17.35 gpm. Temperature of the M/W solution was controlled by means of a heat exchanger located outside the chamber through which the solution could be circulated during pre-test conditioning procedures.

3.4 INSTRUMENTATION

Chamber pressure was measured with ionization and alphatron gages. The IU simulation box and sublimator vent pressures were measured with alphatrons. Transducers were used to measure water and gaseous nitrogen supply pressures. A thermistor was used to measure water temperature at the inlet to the sublimator. Platinum resistance thermometers measured the M/W temperature at the inlet and at the outlet of the sublimator. Test instrumentation is shown in Fig. 13. Instrumentation ranges and overall system accuracies are estimated in Appendix III.

3.5 DATA ACQUISITION AND PROCESSING SYSTEM

Test instrumentation sensor outputs were conditioned, displayed on strip chart recorders, and processed by a 200-channel Dymec® system and stored on punched paper tape. The tapes were later read into magnetic storage on a Scientific Data System 920® computer and processed to provide both tabulated and plotted data.

SECTION IV
PROCEDURE

4.1 DETERMINATION OF THE IU INTERNAL PRESSURE DURING OPERATION OF THE SUBLIMATOR

An IU simulation box was scaled, designed, built, and installed in the test chamber so that the vent area required for the actual IU could be determined. Two different vent areas (200 and 100 in.^{2}) were tested. For each vent area tested, the chamber was evacuated to the 10^{-4} to 10^{-5} torr pressure range, and the sublimator was

activated. Upon evidence of a "start" of the sublimator, a simulated outgas load was initiated to the IU "box" and was continued until steady-state conditions were attained in the IU box. Various outgas loads were simulated, and the resulting pressures were plotted as seen in Fig. 15. During the time that large amounts of GN_2 outgas simulation loads were being placed on the system, the 120-ft^2 20°K gaseous helium cryosystem was used. However, during the majority of the test program the diffusion pump and LN_2 cryosystem were sufficient to handle the gas and water vapor loads and maintain choke flow across the IU simulation box vent plates.

4.2 DETERMINATION OF SUBLIMATOR PERFORMANCE CHARACTERISTICS AND OPERATING LIMITS

The operating limit for any particular sublimator is defined as a set of conditions at which the sublimator would not start but would break through - the result of either excessive heat load, excessive internal water pressure, or both. To determine the operating limits of a sublimator, it is necessary to set heat load and water supply conditions, activate the sublimator, monitor the various parameters relating to its operation, and determine whether it would start or break through. The heat load was controlled by varying the temperature of the M/W solution while maintaining a constant flow rate of 17.35 gpm (7800 lb_m/hr). The internal water pressure was controlled by regulating the pressure on the water accumulator (bladder pressure). A test run would generally take 10 to 15 min. Runs were continued in this manner until a definition between the "good start" zone and the "breakthrough" zone was made as seen in Fig. 6. In general, successive good starts were achieved with incremental increases in bladder pressure and relatively steady heat load conditions until a breakthrough occurred. Then another heat load condition was probed with step by step increases in bladder pressure until another breakthrough occurred. Three heat load conditions were probed as seen in Fig. 6. The direction of testing was usually from the lower to the higher internal water pressure levels. Some 20 separate test runs were usually required before a good definition of operating limits could be made.

After each run, it was necessary to "dry out" the sublimator. This generally took 20 to 30 min after a "good start" test run. Minimum evidence of a dried out sublimator was an internal pressure of near 0 psia as sensed by the water inlet pressure transducer shown in Fig. 13. Further evidence of a dry sublimator was a zero M/W solution temperature drop across the sublimator, i.e., no refrigeration effect. After a breakthrough had occurred, there was generally a rather large volume of ice present in the sublimator vents. Since it was necessary to remove this ice before another run was made, the process was accelerated by

bleeding dry nitrogen gas into the IU simulation box to raise the total pressure above 4.6 mm Hg, the triple point of water, and by providing heat through strip heaters attached to the bottom of the box.

Also of interest was the refrigeration capacity of each sublimator at design conditions. This was usually checked at the first of a series of test runs and again at the last. The procedure was simply to start the sublimator and measure its cooling capacity at a certain heat load condition, 63.7°F M/W inlet temperature and 7800-lb_m/hr flow rate. The refrigeration effect was checked again at the last of the test series to determine if any degradation of capacity had occurred during the test program.

4.3 FLIGHT PROFILE SIMULATION

Reliable performance of ECS is as dependent upon the operation of the GN_2 pressurization system as it is upon the characteristics of the sublimator itself. Therefore it was necessary to make one final evaluation of each sublimator coupled with a typical flight GN_2 pressurization system.

The pressurization system used consisted of a 16-psia GN_2 source (located outside the test chamber) and an orifice regulator which serves to vent the bladder during the ascent of the vehicle and also maintains a bladder pressure of 5 psia during the operation of the sublimator. This orifice regulator is located just below the flight accumulator and for the purposes of the test was vented through a valving arrangement outside the test chamber and back again into the chamber. A GN_2 supply of 16 psia was set up to flow through the orifice regulator (see Fig. 14) and was vented to atmosphere just before the profile test run. At "time zero" the 16-psia supply, along with the bladder, was vented to the chamber, and the flow was throttled to provide the desired decrease in bladder pressure (flight profile). At a specified point in the "time of flight" the water solenoid valve was opened, thus activating the sublimator. If the orifice regulator malfunctioned or did not perform in the proper manner, an excessive bladder pressure would exist at the moment of sublimator activation and during fill and would probably result in a breakthrough.

After the flight profile simulation test and a final refrigeration capacity check, the sublimator was removed from the test chamber, inspected, and returned to NASA. Data were processed, and an evaluation of each sublimator was made based on the parameters shown in Fig. 16.

SECTION V
RESULTS AND DISCUSSION

Thirteen sublimators were evaluated in this test program. Ten of these are designated as flight-scheduled sublimators. The other three were used as development test articles. Test results in the forms of tabulated data, starting condition limit plots, and refrigeration capacity plots have been grouped for each sublimator and are presented in Figs. 17 through 59.

A special test data report has been compiled containing detailed test data of each individual test run made on each sublimator in addition to that data outlined above. Because of its bulk (456 separate test runs were made), this special test data report will not be given general distribution.

5.1 DETERMINATION OF IU INTERNAL PRESSURE DURING OPERATION OF THE SUBLIMATOR

Sublimator SN9, the first unit tested, was used to determine the IU internal pressure during sublimator operation. The SN9 was operated with IU outgas simulation loads of 10, 30, and 50 lb_m/hr with an IU simulation box vent area of 200 in.^{2}. The IU box vent area was then reduced to 100 in.^{2}, and the sublimator was operated again for the same outgas simulation loads of 10, 30, and 50 lb_m/hr. Figure 15 shows the relationship of the two vent areas with respect to outgas load and steady-state IU background pressure. The 100-in.^{2} vent area was seen to be adequate in maintaining IU pressures well below that of the triple point of water since the expected gas load into IU is 30 lb/hr.

5.2 DETERMINATION OF SUBLIMATOR PERFORMANCE CHARACTERISTICS AND OPERATING LIMITS

The most critical point in the operation of the sublimator is the time when the sublimator is being initially filled with water. The sublimator experiences a heat load from the moment the vehicle leaves the launch pad and therefore must fill and start under thermal load.

The most comprehensive indicator of sublimator performance is the time profile of the water inlet pressure. As seen in Fig. 16, during the initial phase of fill, certain flow restrictions in the line between the water accumulator and the sublimator inlet tend to keep the water inlet pressure low. As the unit fills, conductance through the porous plates becomes a more dominant factor, causing the inlet pressure to rise. If the operation results in a good start, the final water inlet pressure

will be maintained. However, if the operating limits have been exceeded, a breakthrough will result, as will be indicated by a rapid drop in the water inlet pressure along with a rapid increase in water flowrate. Breakthrough will be verified within a few seconds by the observance of a large ice formation in the exhaust vents (Fig. 5).

The water inlet pressure and the M/W solution inlet temperature at the completion of fill (Fig. 16) defined the data point plotted in the critical starting conditions curve. Breakthroughs occurred as much as 11 min after fill was completed and at conditions which were (at that time) well within the region of good starts. This indicates that the initial formation of the ice layer in the porous plates which is necessary for a good start is critically dependent on the conditions at the completion of fill.

If these conditions during fill, and especially just at the completion of fill, are such that a "weak" ice layer is formed within the porous plates, this will result later in a breakthrough even though the conditions (M/W inlet temperature) have dropped well within the good start zone.

Refrigeration capacity was checked for each sublimator at 63.7°F M/W inlet temperature. At this heat load, 9-kw refrigeration capacity should be achieved to meet design specifications. Some degradation in refrigeration capacity was noted during the course of a test. This was thought to be the result of an accumulation of contaminants in the porous plates which restricted water flow and therefore sublimation rate. This degradation is not attributed to contaminants in the water used to fill the accumulator, as no particles greater than 50 microns were present.

Flight profile simulation runs were made on all units tested except SN9 and 10. The units functioned normally when operated under simulated conditions using a 16-psia GN_2 supply pressure to the orifice regulator. Some results obtained in various simulation runs are presented in the following discussions of the performance characteristics of each sublimator tested.

5.2.1 SN10

Although SN10 was one of the external venting sublimators, it was mounted inside the IU simulation box and operated in the internal venting mode. Fifty-six runs were made to define the operating limits of the sublimator. A sharp definition of the critical starting conditions curve was not accomplished in this first series of tests, possibly

because a good testing technique had not been fully developed. Critical starting conditions were determined with a flowmeter in the waterline and later when the flowmeter had been removed from the line. The effect of the flowmeter on starting conditions is seen in Figs. 17 and 18, the critical starting conditions curves. As shown, these conditions are more limited when the flowmeter is not in the line.

Refrigeration capacity at design conditions was adequate. However, as seen in Fig. 19, some degradation was noted in the later runs (42-55) and prompted another series of test runs using this sublimator (see Section 5.2.5).

The effect of air bubbles in the water supply system was investigated. Air, at rates up to 3.5 atm cc/min, was bled into the water supply line with no adverse effect on the sublimator performance.

The effect of a high temperature (110 to 120°F) water supply was also investigated. The sublimator did not break through; however, the completion of fill was clearly distinguishable by the water pressure indicator. Net refrigeration capacity was lower (as much as 0.5 kw) because of the amount required to cool the water down to the mean sublimator operating temperature. In two of the three runs (54 and 55, Fig. 19) which were made at the high water temperature, refrigeration capacity was below design specifications. If the sublimator did not completely fill, all the sublimating (porous plate) area would not have been utilized, and this would have resulted in a lower refrigeration capacity.

5.2.2 SN9

Sublimator SN9 was also one of the external venting sublimators tested in the internal venting mode. Critical starting conditions were determined with a flowmeter in the waterline and later without a flowmeter. The "without (W/O) flowmeter" configuration was slightly more critical than the "with flowmeter" configuration. As seen in Figs. 20 and 21 a sharper definition of the critical starting conditions curve was accomplished than with SN10.

The refrigeration capacity was marginal at design conditions (see Run 11, Fig. 22). A slight degradation was also indicated in two of the last four runs.

5.2.3 SN4′

The first of the modified or internal venting sublimators tested was SN4′. The "prime" designation in the numbering system indicates a

modifier sublimator. This unit was installed as shown in Fig. 12 and tested with a water inlet orifice 0.068 in. in diameter, compared with 0.078 in. used in the previous two sublimators tested. Fifty-six runs were made with the 0.068-in. orifice. The effect on performance of a horizontal sublimator orientation (Fig. 12) was investigated. The orifice was enlarged to 0.078-in. diameter, and 18 more runs (Figs. 29) through 31 and SN4 test data) were made both with and without a flowmeter in the waterline. However, no more horizontal orientation runs were made with the 0.078-in. orifice.

Little difference was noted in the refrigeration effect with respect to orifice size and waterline configuration (with or without flowmeter). Orientation had a noticeable effect on the operation of the sublimator. Horizontal operation of the unit resulted in a 15 percent longer fill time. In this position, water flowed over and sublimated through the entire surface of porous plates in the lower modules during the first half of fill, resulting in higher refrigeration effects during fill and hence longer fill time. Sharp definition of the critical starting conditions curve was not accomplished. Data indicate that the ability of the sublimator to start seems to be dependent upon past history. After successive breakthroughs (Runs 42 and 43, Fig. 25), the sublimator would not start but broke through (Run 44) in the zone which had previously been defined as being reliable for good starts. This tendency became apparent as the test program progressed and is believed to be a result of some sort of cleansing action taking place within the porous plates during a breakthrough, making the sublimator more porous and susceptible to breakthrough.

There was again a gradual performance degradation observed as run time accumulated on the sublimator (Fig. 28). Note the low run numbers on the high side of the average performance curve and the high run numbers on the low side. Degradation was small (3 percent). In most of the remaining sublimator evaluation tests, a comparison of performance between initial and final runs near 63.7°F M/W inlet temperature (design conditions) was made.

As expected, fill time was affected by the various waterline configurations. Filling was completed approximately 30 percent faster with an 0.078-in. orifice than with the 0.068-in. orifice. There is a 30.5-percent increase in area between 0.068- and 0.078-in.-diam orifices. Presence of a flowmeter in the line increased fill time by 20 to 25 percent.

5.2.4 SN3′

Starting characteristics of SN3′ were noticeably affected by sublimator orientation and the water supply line configuration. Data taken during the runs made without a flowmeter with the unit mounted in the vertical position (Fig. 33) show that the starting limitations are dependent primarily upon pressure and not heat load. This was also the case for the test runs made when the unit was in the horizontal position, except that the maximum water pressure allowable for a good start was approximately 1 psia lower, as seen in Fig. 35. Considering the results of tests run with a flowmeter installed, a more limited start regime exists when the unit is mounted in the horizontal position as shown in Figs. 32 and 34. A final series of test runs was made with the unit again mounted vertically with little change in starting condition limits.

Runs 35 through 40 were made with a water supply temperature of 115°F, caused by leaving the IU simulation box heaters on too long. Runs 35 through 37 were not successful because of a vapor lock in the water supply line. Little effect was noted in the critical starting conditions curve (Fig. 33) because of the elevated water temperature. The refrigeration capacity, however, did show a decrease compared to previous runs (Runs 32 and 34, Fig. 37) made under similar conditions but with lower water temperature. This would be expected with the added heat load contributed by the water (see Section 5.2.1).

Successive flight profile runs were made with 16-, 10-, and 21-psia GN_2 supply pressures, respectively. Breakthrough occurred during the run made when a 21-psia GN_2 supply pressure was used. This illustrates the limited response of the orifice regulator. With an excessive supply pressure on the bladder, the regulator could not vent the bladder fast enough to prevent breakthrough. This condition could have been avoided by waiting and allowing additional time for the bladder to vent before opening the water solenoid valve to the sublimator.

This series of tests revealed another characteristic of the water accumulator. The bladder pressure, 30 sec after the solenoid was opened, was higher with the 10-psia GN_2 supply pressure used in Run 42 than with the 16-psia supply pressure used in Run 41. This resulted from conditions existing in the water supply system before either run started. Before the start of each day's testing, the water accumulator was filled and capped off, leaving approximately 50 atm cc's of air under the accumulator cap and approximately 2.5 atm cc's of air in the waterline between the accumulator and the solenoid valve. When the solenoid was opened for the first run, this entrapped air vented

immediately through the sublimator, thus relieving some of the pressure on the bladder. Run 41 demonstrated that venting the trapped air in the water accumulator and line would relieve the bladder pressure from 6 to 3 psia, 1.4 psia below the steady-state pressure supplied by the orifice regulator. However, in Run 42 this capability for rapid venting no longer existed since the waterline and fill cap were full of water. Therefore even with a lower GN_2 supply pressure at the start of the profile run (Run 42), the bladder pressure did not decrease as low as it did in Run 41.

In the 16-psia run the bladder pressure decreased to 6 psia in 150 sec. A 3-psia drop then occurred as the solenoid was opened. Applying this data to a 21-psia run under the same conditions, the pressure at 150 sec should be no greater than 11 psia and 8 psia after the solenoid is opened. Allowing an additional 2-psia decrease during fill, the bladder pressure should be sufficiently low to provide a good start.

A gradual performance degradation in terms of refrigeration capacity was apparent as total run time on the unit accumulated (Fig. 37). This is similar to the degradation effect noted in the previous sublimators tested. However, this degradation seemed to level off after some 40 runs and remained above the refrigeration capacity specified by NASA even through Run 74.

The cause of this degradation effect can only be speculated. Stringent cleanliness requirements were specified for the water used to fill the accumulators, and these requirements were met and maintained throughout the entire test program. Even so, it is possible that a small surface residue built up on the plates over the operating period. In general, a degradation in refrigeration capacity was accompanied by an increase in the good start region, i.e., the sublimator became less critical and breakthrough less likely. This is further indication of an accumulation of contaminants from some source within the porous plates.

5.2.5 SN10 (Repeat Tests)

The SN10 sublimator was returned for additional testing. Another series of tests was made to define the critical starting conditions. This time only the "without flowmeter" waterline configuration was used. In general, a less restrictive starting conditions region was defined (Fig. 38) than with the original series of tests (Fig. 18 and Section 5.2.1).

The refrigeration capacity was still lower than that experienced early in the first series of tests as discussed in Section 5.2.1. The refrigeration capacity was below the design specifications (9 kw at 63.7°F M/W inlet temperature), but the trend toward a further loss in capacity leveled off.

This indicates that refrigeration capacity may degrade to a certain level as run time accumulates and then become independent of additional operating time.

5.2.6 SN5′

There was again a noticeable difference in the starting characteristics between the with flowmeter and without flowmeter configurations (Figs. 40 and 41). Good start curve definition was obtained without the flowmeter installed, and the curve appeared to be insensitive to temperature above 80°F. Below that temperature, greater sensitivity to heat and less sensitivity to pressure was indicated. A larger start region was defined with this unit than with other sublimators tested.

During the with flowmeter tests, two breakthroughs (Runs 12 and 13, Fig. 40) were observed in the region of good starts which had already begun to be established, especially by Runs 7 through 10. The tabulated data for SN5′ (Appendix II) indicate that these two breakthroughs occurred before completion of fill. When compared with Runs 11 and 15, for the bladder pressure that existed, the water pressure did not reach the level that it should have to indicate completion of fill. Therefore, the line shown above points 12 and 13 represents the level that the fill pressure should have reached, based on pressure drop data from previous runs. This occurred several times throughout the test program, although not always to this degree.

The refrigeration capacity again decreased as operating time on the unit increased (Fig. 42). However, toward the end of the test a recovery of the original refrigeration capacity values was evidenced. No explanation of this recovery is apparent.

5.2.7 SN7′

The influence of the flowmeter on the starting characteristics was again apparent (Figs. 43 and 44) with this sublimator. In all cases but one, that being SN6′ (Section 5.2.9), less critical starting characteristics were experienced when the flowmeter was present in the water supply line. There are two possible explanations for this. The highest flow rate occurs during fill; therefore, with the flowmeter installed, a proportionately larger pressure drop occurs between the accumulator and the sublimator than when the flowmeter is not present. As the sublimator fills, the flow rate decreases, and the effect of the flowmeter on a pressure drop becomes less significant. Tabulated test data for SN7′ give a good comparison. The water inlet pressure at the completion of fill was almost identical comparing Runs 1 and 20, but the

pressure during fill was 3.1 psia higher without the flowmeter than it was with the flowmeter. Another possible explanation of the flowmeter effect might be the pressure transient and the associated heat flux transient. Longer fill times were noted when the flowmeter was present in the water supply line. The pressure transient and heat flux transient directly affect the formation of the ice layer and the flow of water through the sublimator. The longer fill times should result in less severe pressure transients, thus allowing for a better ice layer formation, and thereby ensure against breakthroughs.

Refrigeration capacity again decreased with run time to a certain level and then appeared to recover some of its original capacity (see Fig. 45).

The effect of an additional 10 ft of waterline (between the water accumulator and the sublimator) was investigated in the final test run (Run 25). As would be expected, the pressure drop was greater, as seen in the tabulated test data for SN7′ (comparing Runs 13 and 25). However, the additional length of waterline did not adversely affect the performance of the sublimator.

5.2.8 SN9′

Critical starting characteristics curves (see Figs. 46 and 47) for this sublimator were similar to those defined for SN5′. Good starts were obtained with M/W inlet temperature of 85°F and a fill pressure of 6 psia, twice the 3-psia pressure the unit is expected to see in flight.

Some degradation was again observed in the cooling capacity, as seen in Fig. 48. However, the output was still in excess of the 9 kw specified.

An additional piece of flight hardware was evaluated in the last four runs. This was a high pressure regulator which is used to reduce gaseous nitrogen (stored in a high pressure nitrogen service system in the SIVB stage) from 3000 to 16 psia. The regulator was difficult to set and lock at the desired pressure setting, but it operated satisfactorily after the desired setting was obtained.

5.2.9 SN6′

Virtually no difference was observed in the starting characteristics with and without a flowmeter in the water supply line (see Figs. 49 and 50). This was the only unit tested which did not indicate a noticeable difference in performance between these two configurations. There

are general indications that the unit became less susceptible to breakthroughs as test time accumulated, as with other units. However, the weakening effect of a breakthrough which was indicated in tests with SN4′ did not occur with this unit.

There was very little cooling capacity degradation throughout this test. This does not substantiate the idea that increased resistance to breakthrough and decrease in cooling capacity might both be caused by deposits in the pores, since the breakthrough resistance increased but there was no loss in cooling capacity (see Section 5.2.4).

5.2.10 SN11′

No further comparison of the starting characteristics with and without a flowmeter was made in the remainder of the test program. Only the starting characteristics curve for the with flowmeter configuration was defined from this point on.

The performance of SN11′ exceeded all units previously tested with respect to starting conditions as well as cooling capacity. No breakthrough was observed below 8 psia (final fill pressure) even at M/W inlet temperatures up to 85°F. As shown in Fig. 52, numerous starts were made with fill pressures near 6 psia. With previous units tested, this value was never exceeded at temperatures as high as 85°F.

Refrigeration capacity was noticeably higher for this sublimator. Initially the capacity at design conditions was 10.9 kw (Fig. 53). In the final run, capacity would have been at least 10 kw had the heat load been allowed to decrease to design conditions.

5.2.11 SN13′

In contrast to SN11′, this sublimator was more limited as far as starting characteristics are concerned (see Fig. 54), however, still acceptable and comparable to other units tested.

The initial refrigeration capacity at design conditions was identical to SN11′, 10.9 kw, and did not decrease throughout the test (Fig. 55).

A new flowmeter was used in this test, and its output was added to the parameters being plotted against run time and is shown in Fig. 60. The water consumption (as determined by the actual weight of water required to refill the accumulator after a day's testing) was compared with the integration of the flowmeter output versus time plots for the same day's testing, and good correlation was obtained.

5.2.12 SN10

The operating characteristics of this unit were similar to those of SN11'. The lowest pressure at which breakthrough occurred was 7.6 psia. This point (Run 12, Fig. 56) was at 77°F, which is midrange of the design temperature limits. It is interesting to note that a good start was obtained later in Run 15 at 7.5-psia final fill pressure but at 84.3°F.

Refrigeration capacity at design conditions was 10.6 kw early in the test series and did not noticeably decrease thereafter (Fig. 57).

5.2.13 SN12'

Nothing unusual was noted in the critical starting condition curve. This was not the case with the refrigeration capacity performance. An appreciable capacity loss was noted between Runs 1 and 12 (see Fig. 59) and an unusual decrease between Runs 12 and 13.

This decrease may correlate with unexpected differences in theoretical and measured water consumption. From a theoretical thermodynamic point of view, the ratio of refrigeration capacity to water consumption is 0.3 kw/lb_m/hr. The measured water consumption during Runs 1 through 12 was 25 percent higher than the theoretical value associated with the measured refrigeration capacity. In Run 13, water consumption was 45 percent higher than theoretical. This is compared with an average of 7 percent above theoretical for previous sublimators tested. No explanation for this has been made. Other test parameters were within the expected limits, and the unit appeared to operate normally. It is recommended that additional testing be conducted on this unit.

5.2.14 SN2'

This unit was subjected to tests designed to establish what, if any, was the minimum heat load at which a sublimator may be operated before a water side freeze rupture would occur. This was done by starting the sublimator at normal conditions and then progressively lowering the heat load for certain lengths of time and then returning to normal heat loads and observing to see if leaks resulted. The heat load was decreased by lowering M/W inlet temperature and also by adjusting M/W flow rate. The sequence of the test is shown in Fig. 61. The test finally came to the condition at which the heat load was totally removed by shutting off the M/W pump for 30 min and then reapplying the normal heat load and checking for leaks (Fig. 62). No damage was evident. Therefore, as a final check, the sublimator was shut off and allowed to dry out,

and another successful fill and start was made to determine if normal performance would result. As seen in Fig. 63, performance was normal. However, refrigeration capacity was slightly below design specifications.

5.3 SUMMARY OF RESULTS

The 100-in.^{2} vent area desired by NASA was demonstrated to be adequate in maintaining IU pressures sufficiently low to permit sublimation. All units tested started successfully below 85°F with a 4.2-psia bladder pressure supplied by the orifice regulator. Above 85°F the units were slow to fill and in some cases would not completely fill. The units would, however, provide refrigeration before completion of fill with a combination boiling-sublimating effect.

The sublimators tested demonstrated thermal efficiencies on the order of 90 percent, i.e., used 5 to 10 percent more water than the theoretical rate associated with the refrigeration effect being produced at the time. This compares with thermal efficiencies from 60 to 70 percent demonstrated by single-pass water-boiler-type environmental control systems used in the Mercury/Atlas program[1].

Refrigeration capacity, at design conditions, varied 20 percent between the upper and lower extremes with only SN12' falling below the 9-kw specifications. Little correlation could be made between the refrigeration output and the ability of the unit to start successfully.

The flight pressurization system tested in the profile runs worked well and demonstrated a good degree of reliability.

No two sublimators performed exactly alike. The various water supply configurations had a significant bearing on the starting characteristics. General comparison of the data shows a significant randomness even for identical test conditions and thus points out the necessity for evaluating each sublimator before flight.

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[1]Buckels, William T. Personal communication relating to test run on the Mercury capsule water boiler at the Applied Mechanical Research Branch, Propulsion Division, Propulsion and Vehicle Engineering Laboratory, George C. Marshall Space Flight Center, Huntsville, Alabama, July 14, 1966.

SECTION VI
CONCLUSIONS

The sublimator is an extremely efficient means of providing a large capacity for refrigeration for limited lengths of time. Even though these particular sublimators were relatively random in their performance characteristics, they are quite reliable within certain critical operating limits. The associated pieces of support hardware and flight instruments designed for ECS are adequate and reliable.

Excessive water supply temperature should be avoided where possible; otherwise some refrigeration effect will be "wasted" on cooling the water.

The microscopic nature of the sublimator performance is not fully understood. Further testing in this area is recommended. Until this basic understanding is determined, it will be necessary to flight-evaluate each sublimator.

APPENDIXES

I. ILLUSTRATIONS
II. NASA SATURN SUBLIMATOR TEST DATA
III. ANALYSIS OF INSTRUMENTATION ERROR

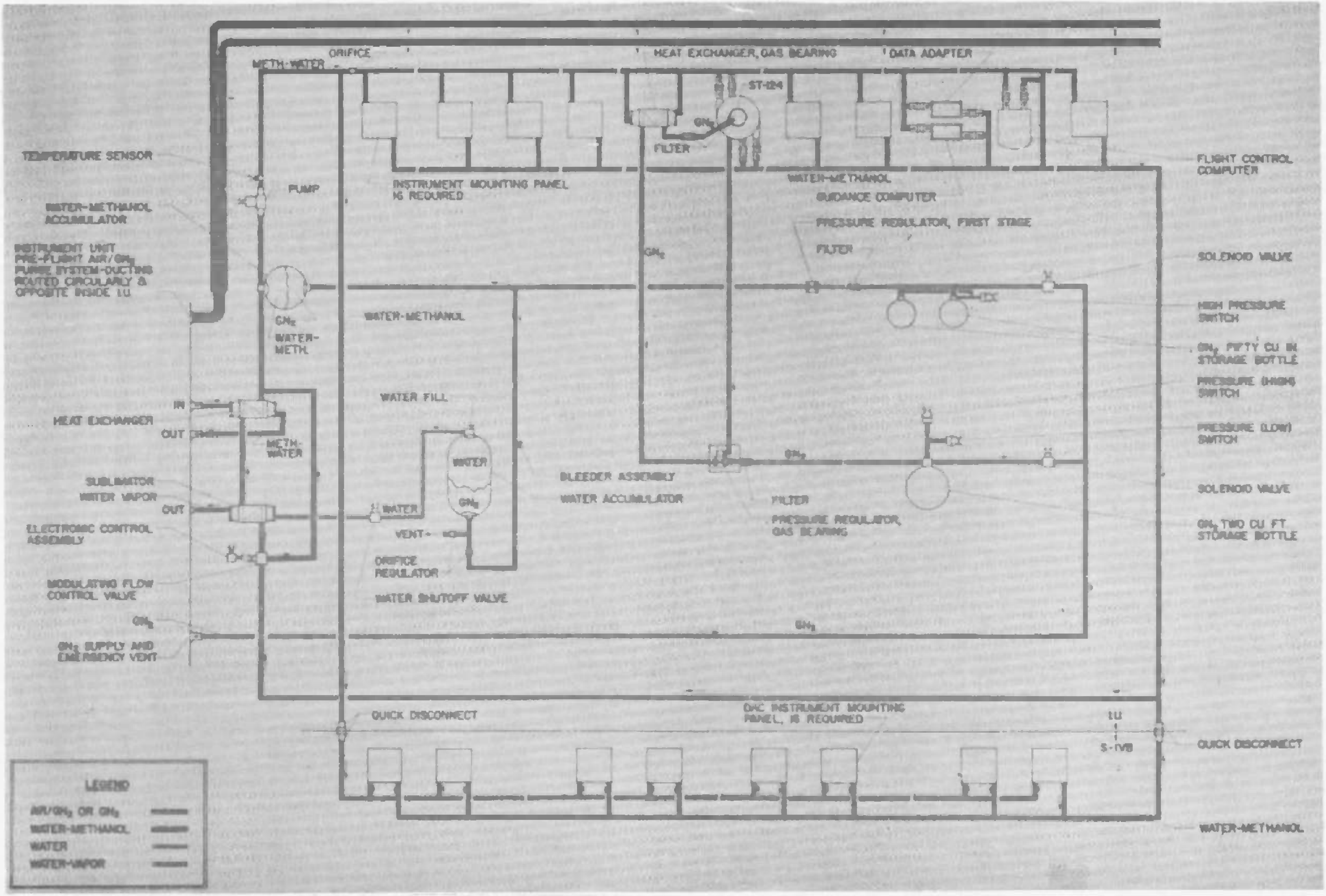


Fig. 1 Schematic of IU Environmental Control System

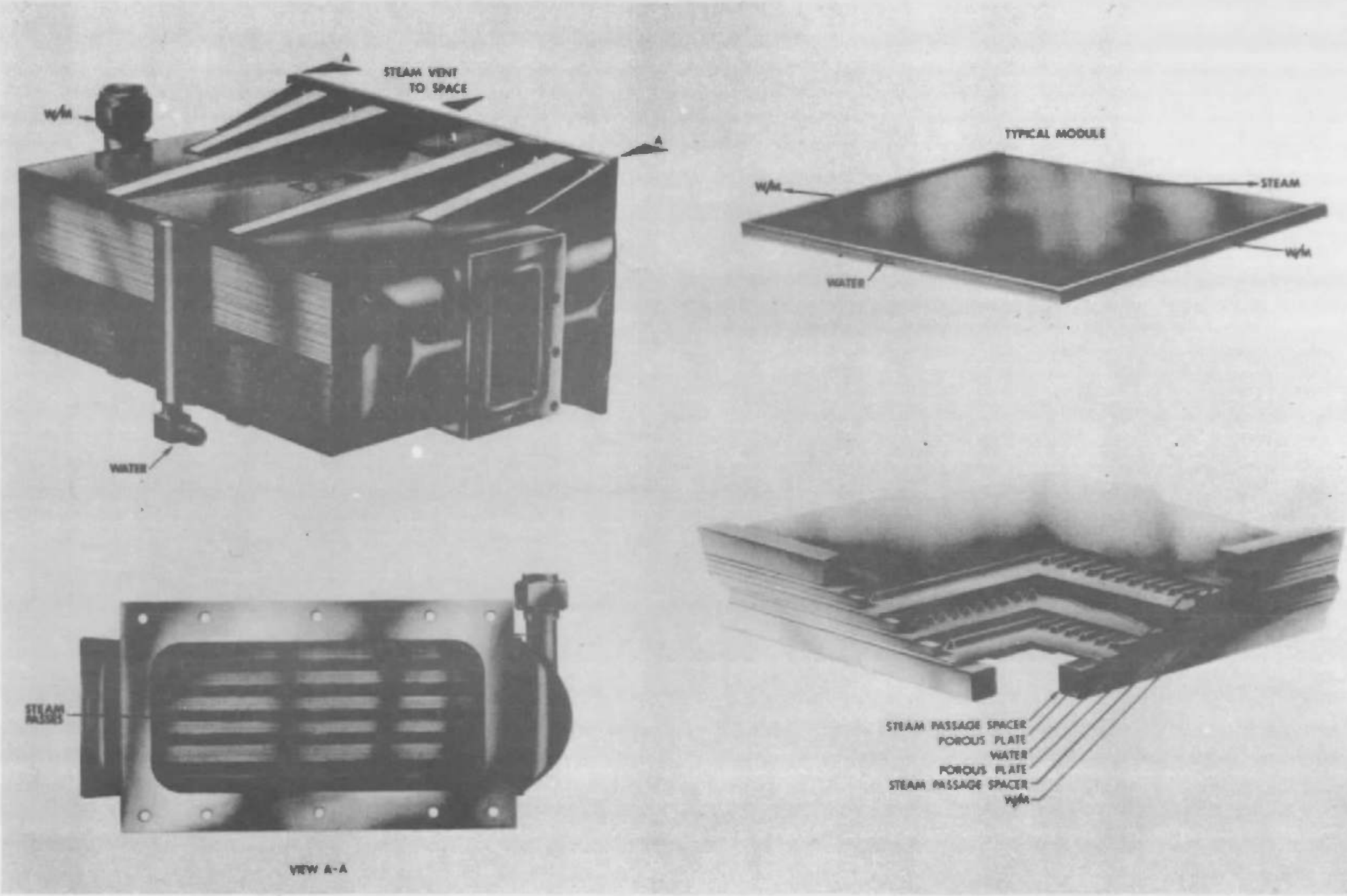


Fig. 2 Cutaway View of the Sublimator

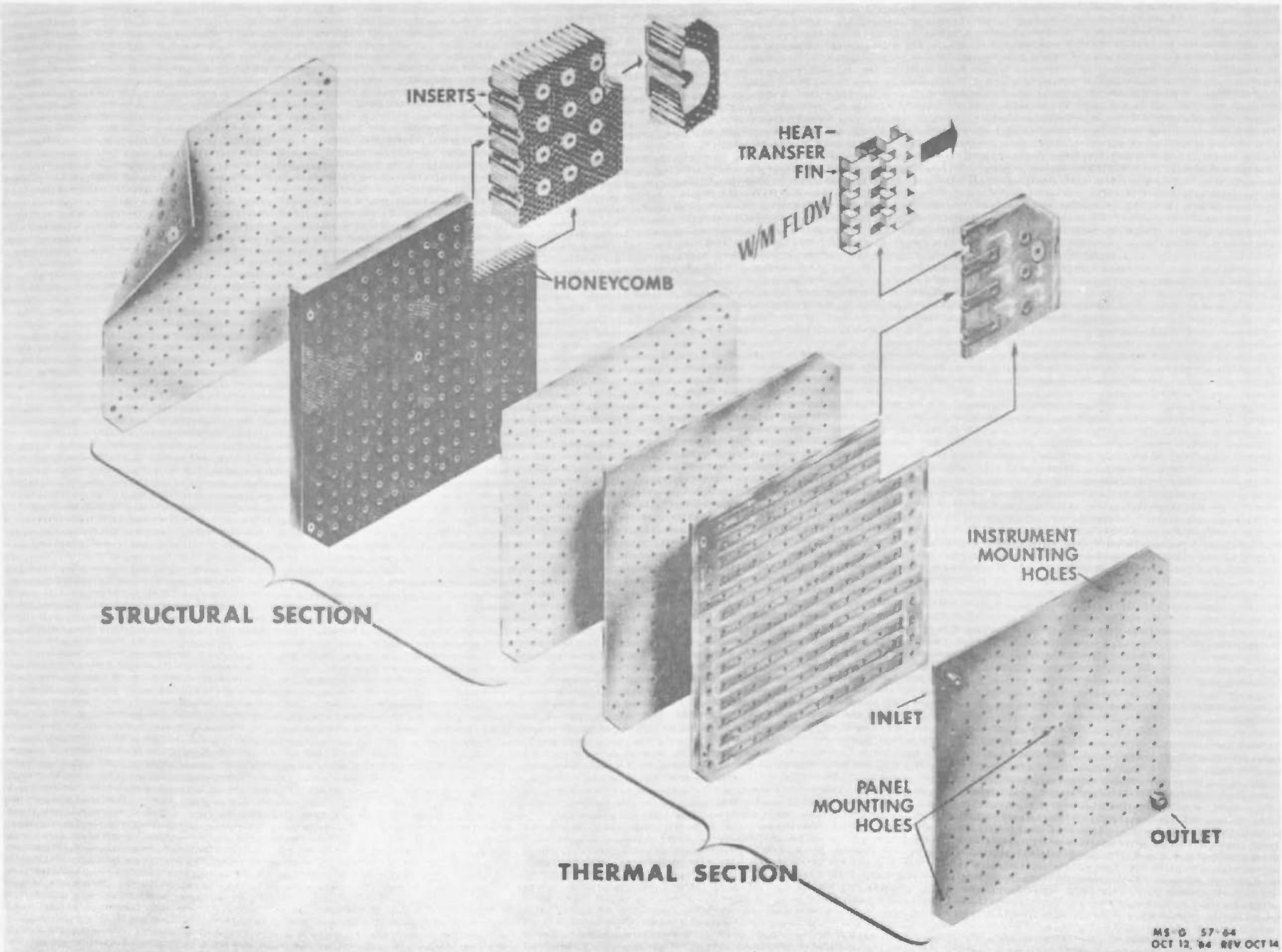


Fig. 3 Mounting and Thermal Conditioning Panel

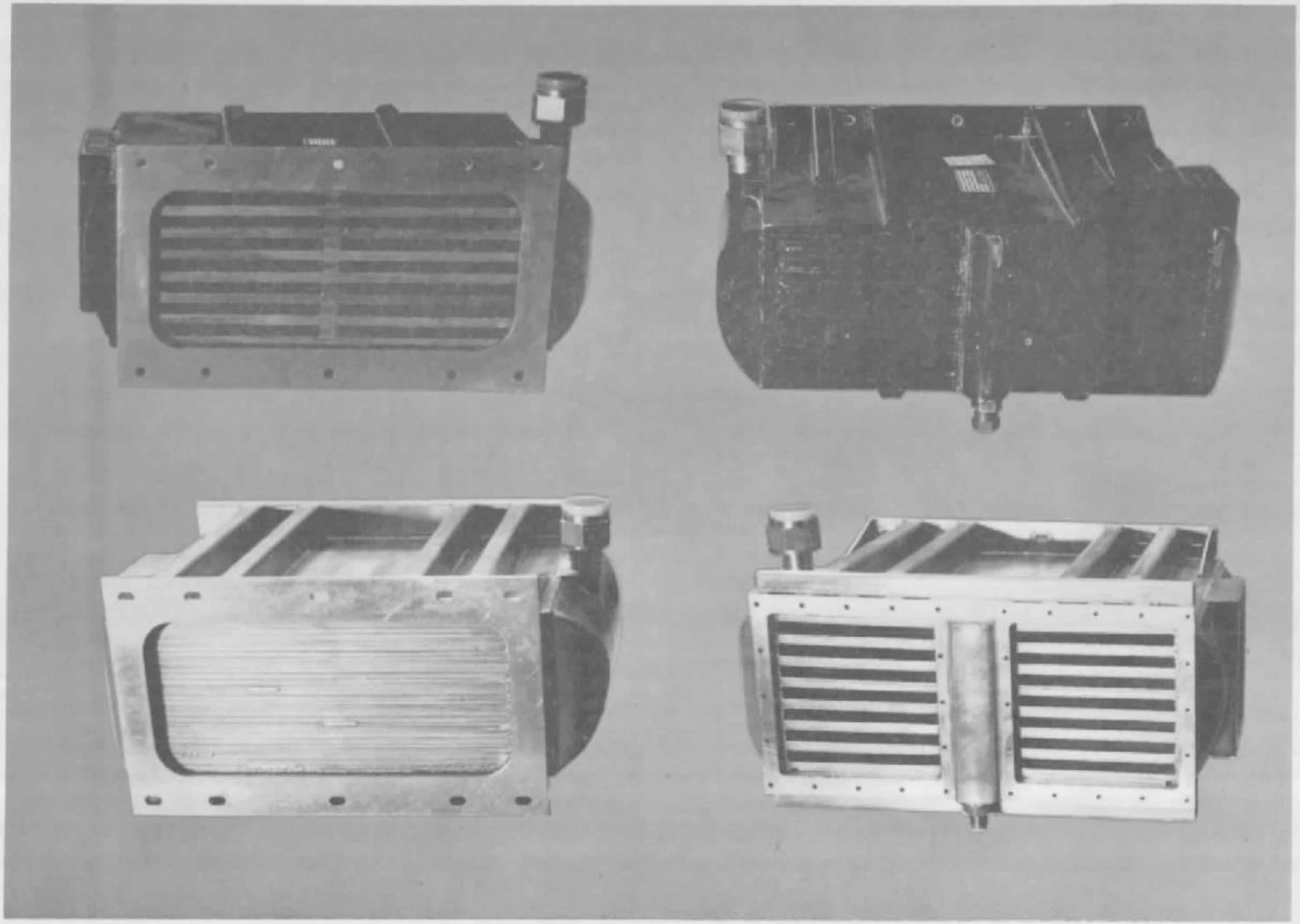


Fig. 4 Original and Modified Sublimators with Pre-Flight Heat Exchangers

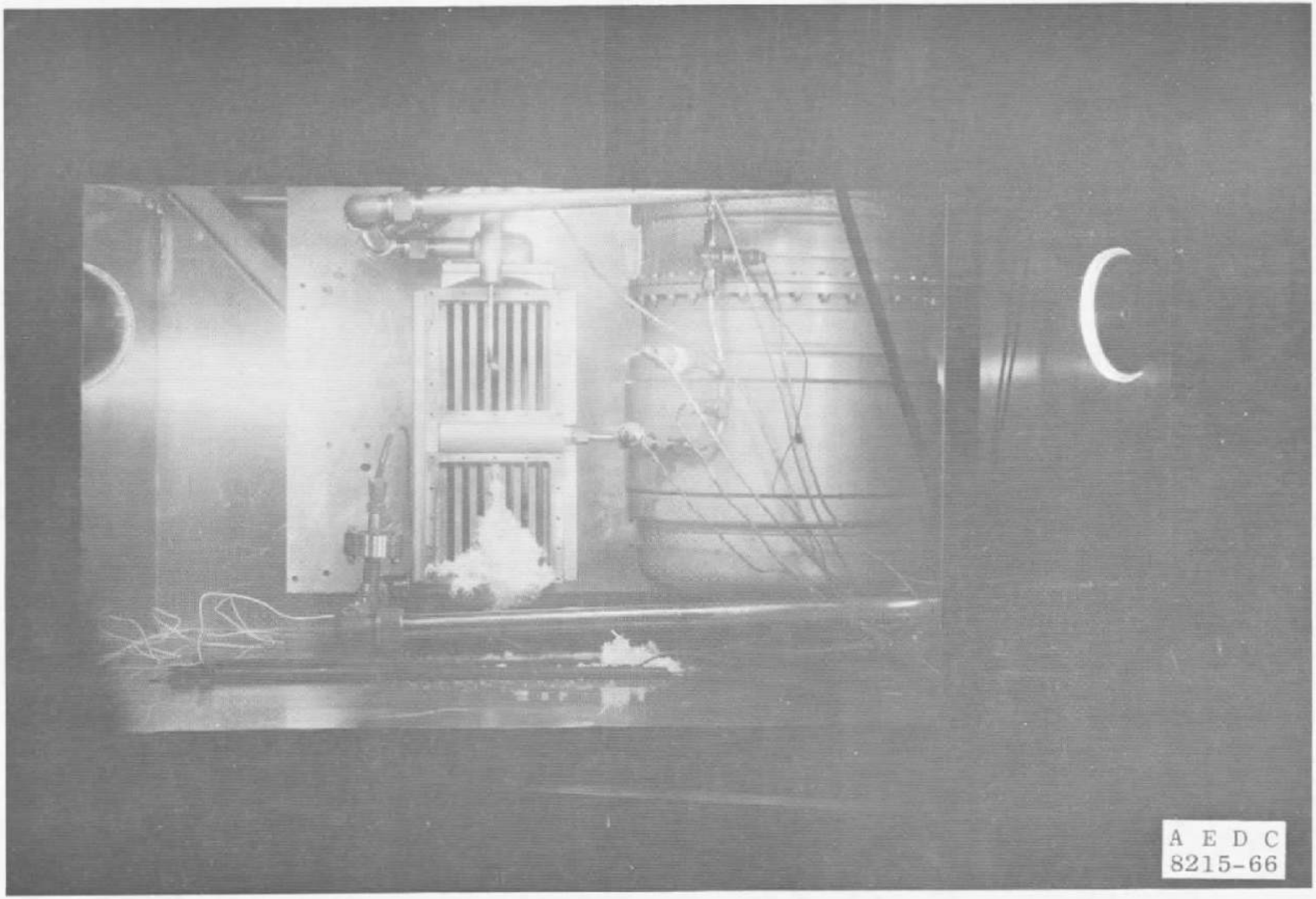


Fig. 5 Sublimator Breakthrough

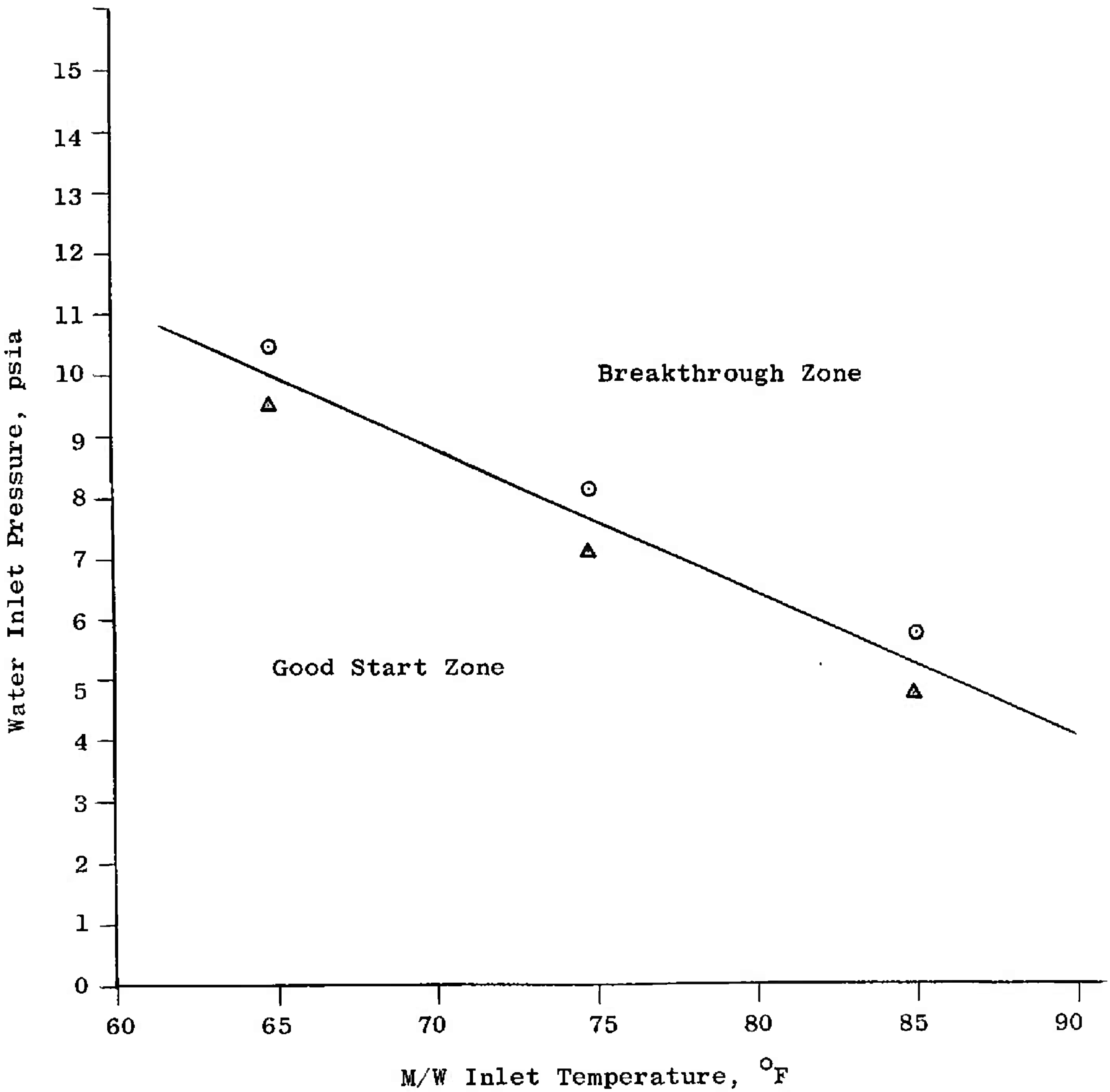


Fig. 6 Critical Starting Conditions Definition Curve

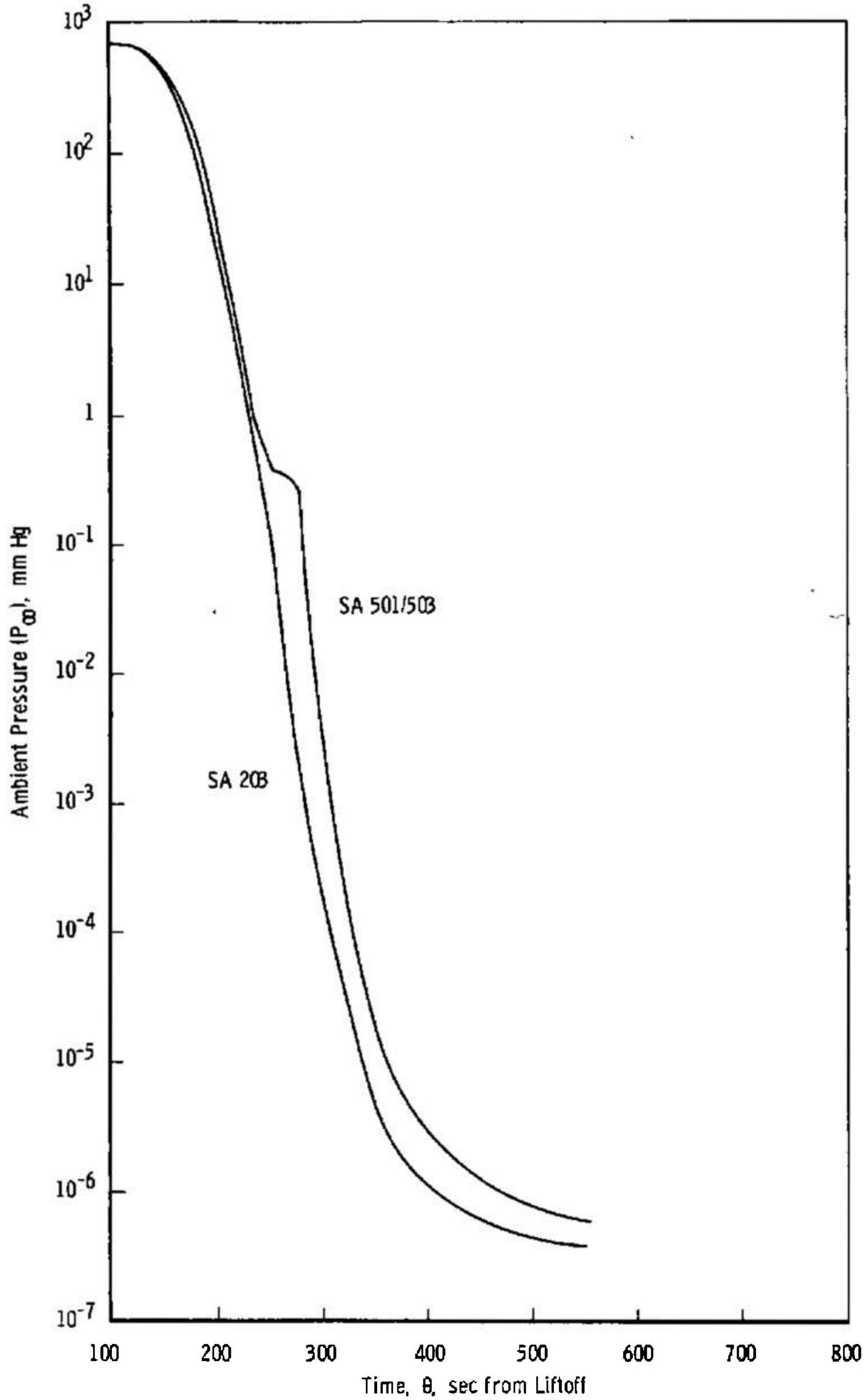


Fig. 7 Saturn Launch Profile

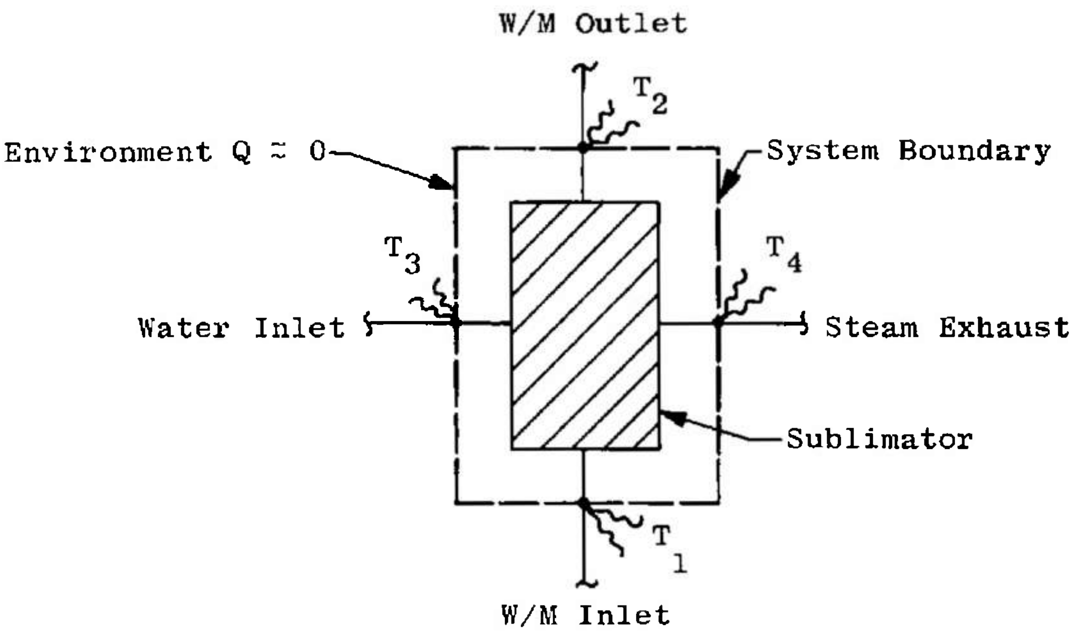
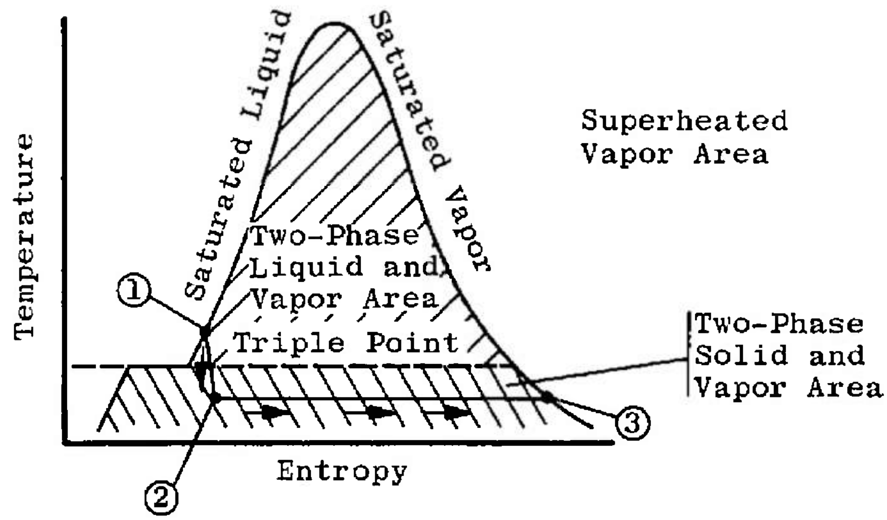
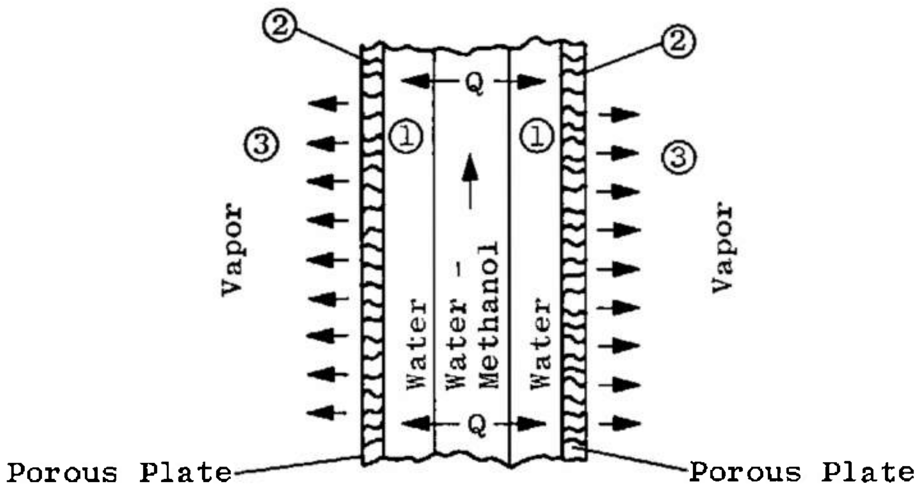


Fig. 8 Basic Thermodynamic System Diagram



Temperature-Entropy Diagram for Water



Module Cross Section

Fig. 9 Temperature-Entropy Diagram for Water; Sublimator Module Cross Section

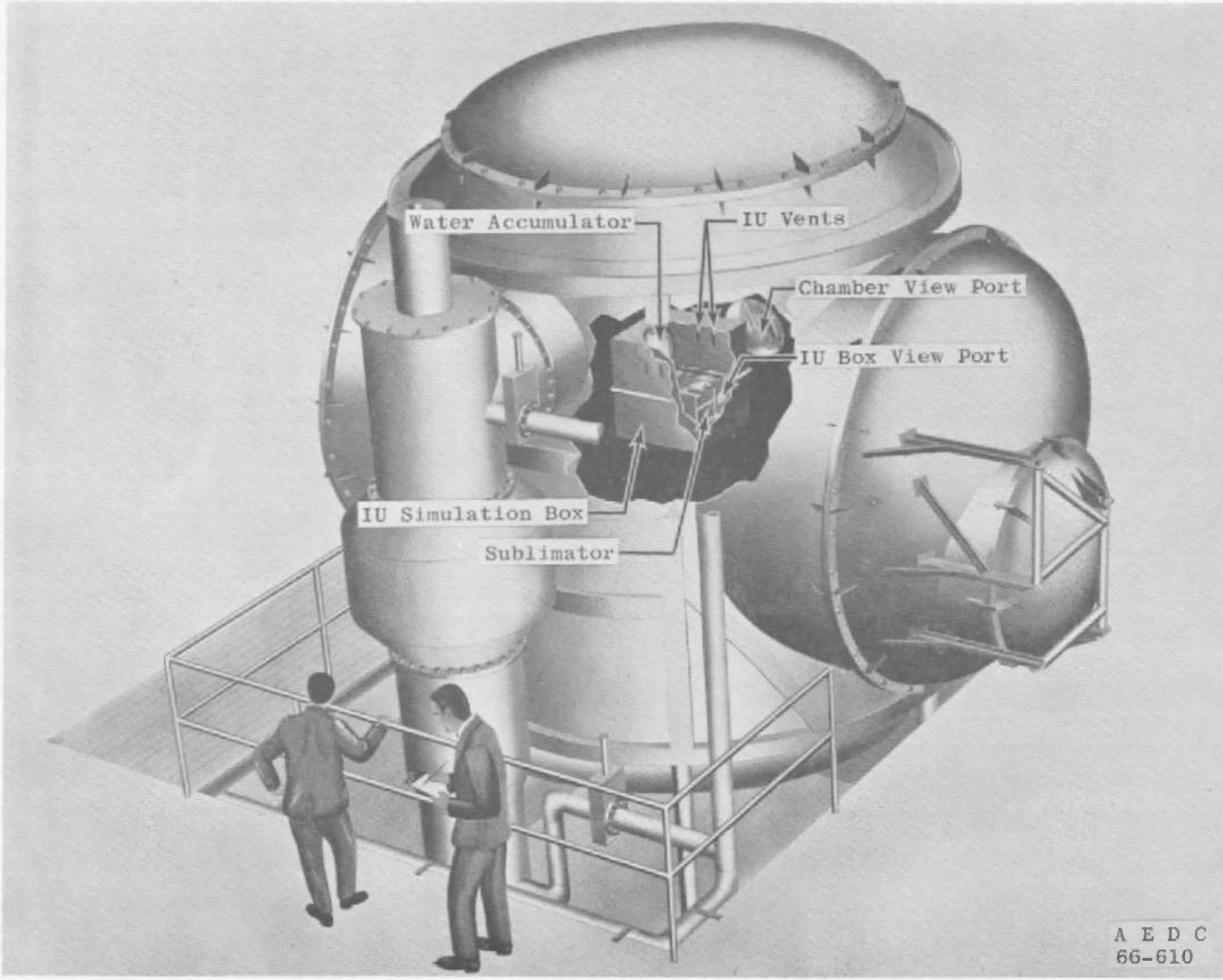


Fig. 10 Sublimator Test Installation in ARC (12V)

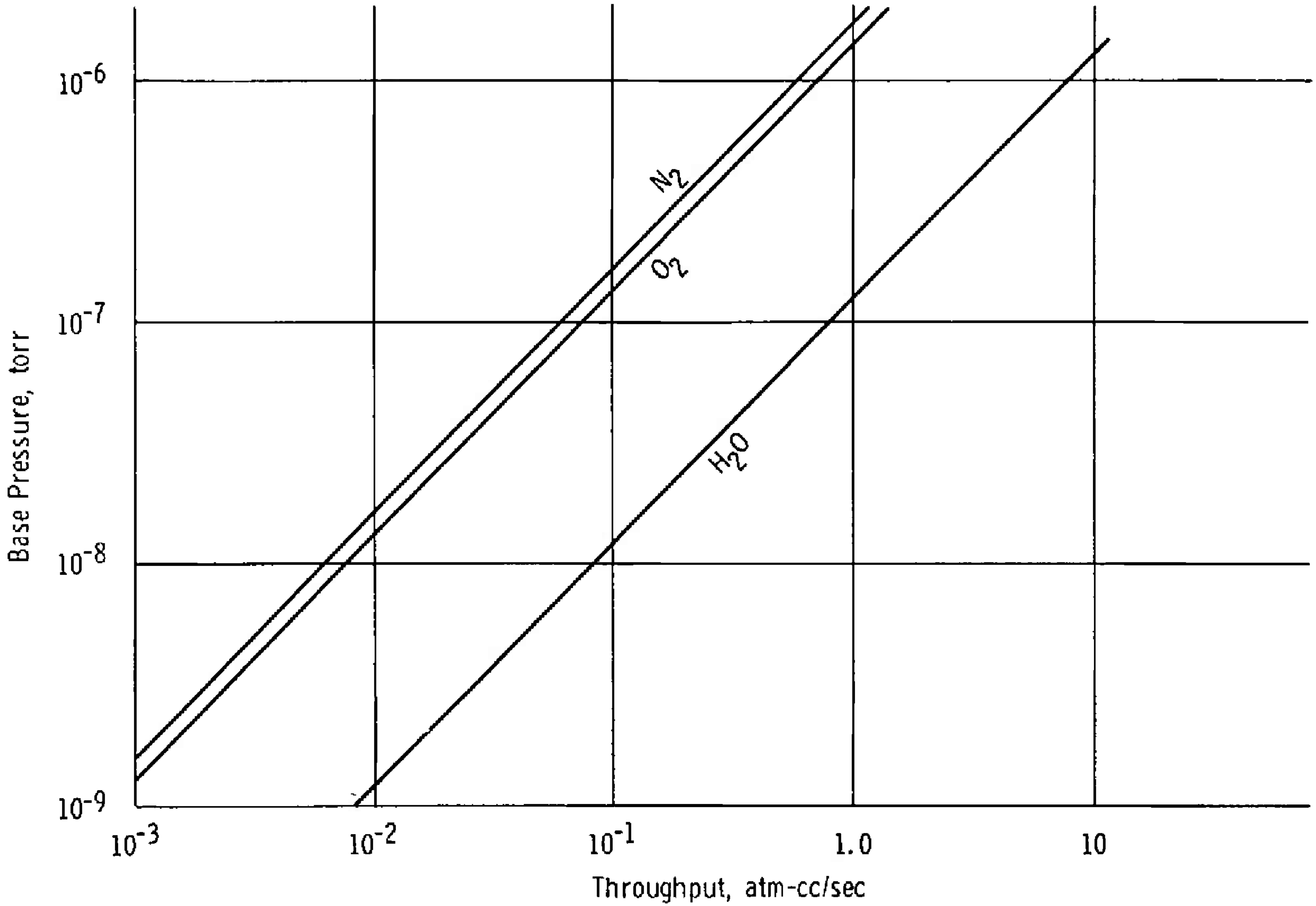
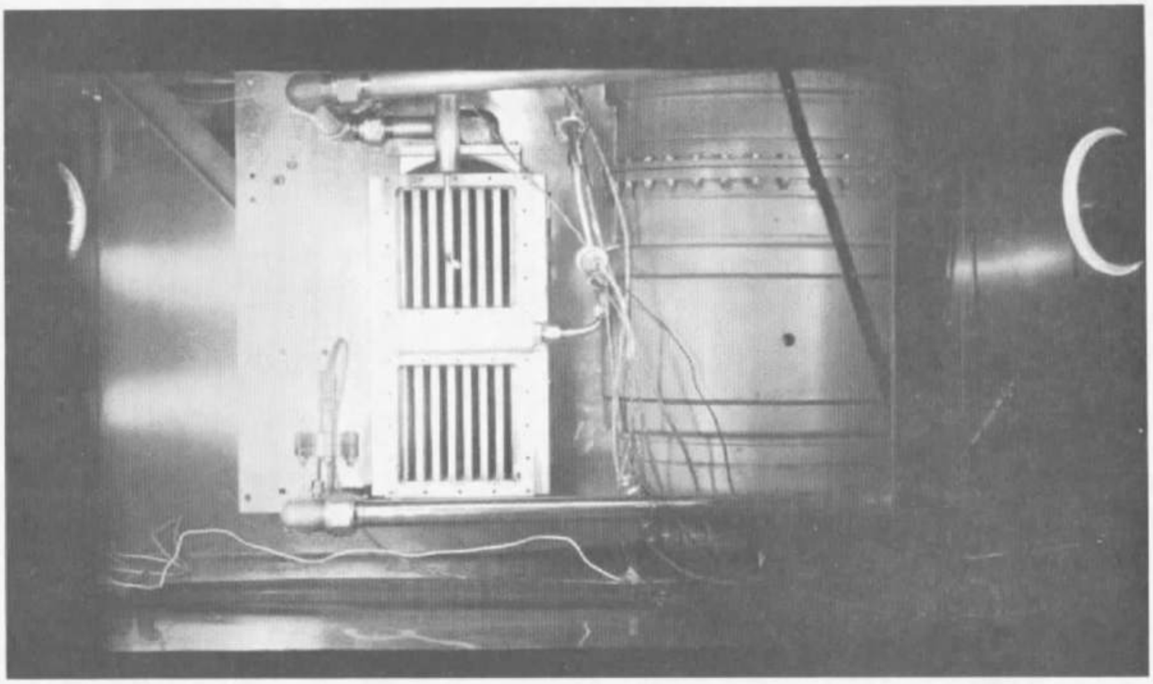


Fig. 11 Performance of ARC (12V)



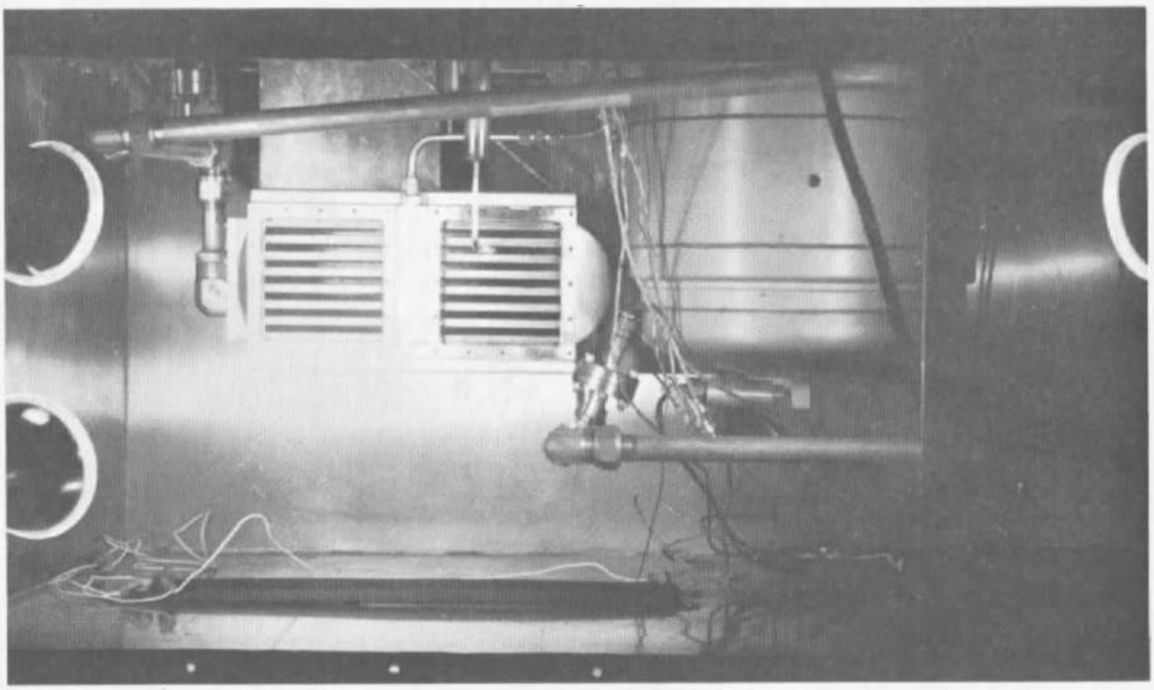


Fig. 12 Sublimator and Water Accumulator Test Installations inside IU Simulation Box (Vertical and Horizontal)

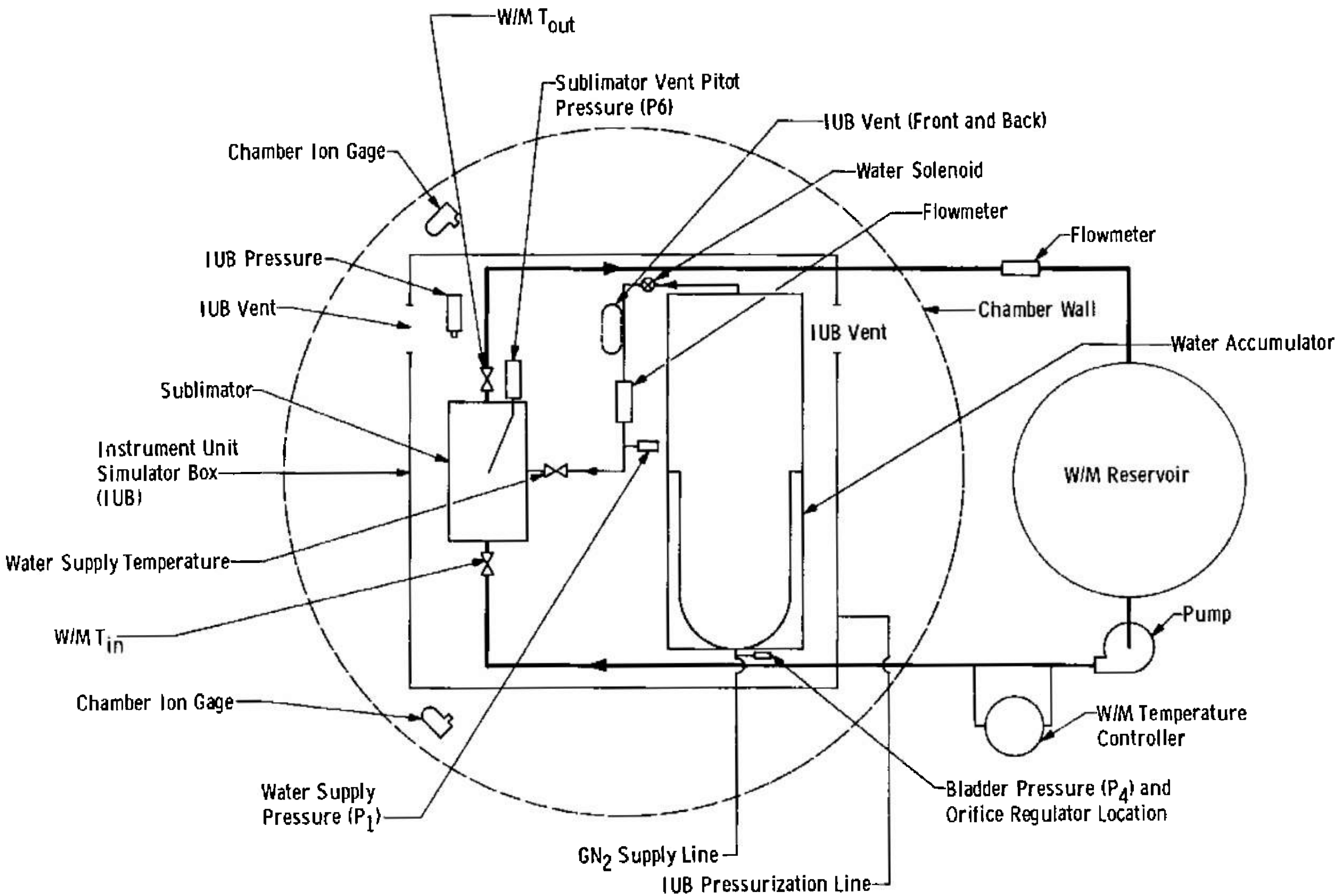


Fig. 13 Test and Instrumentation Schematic

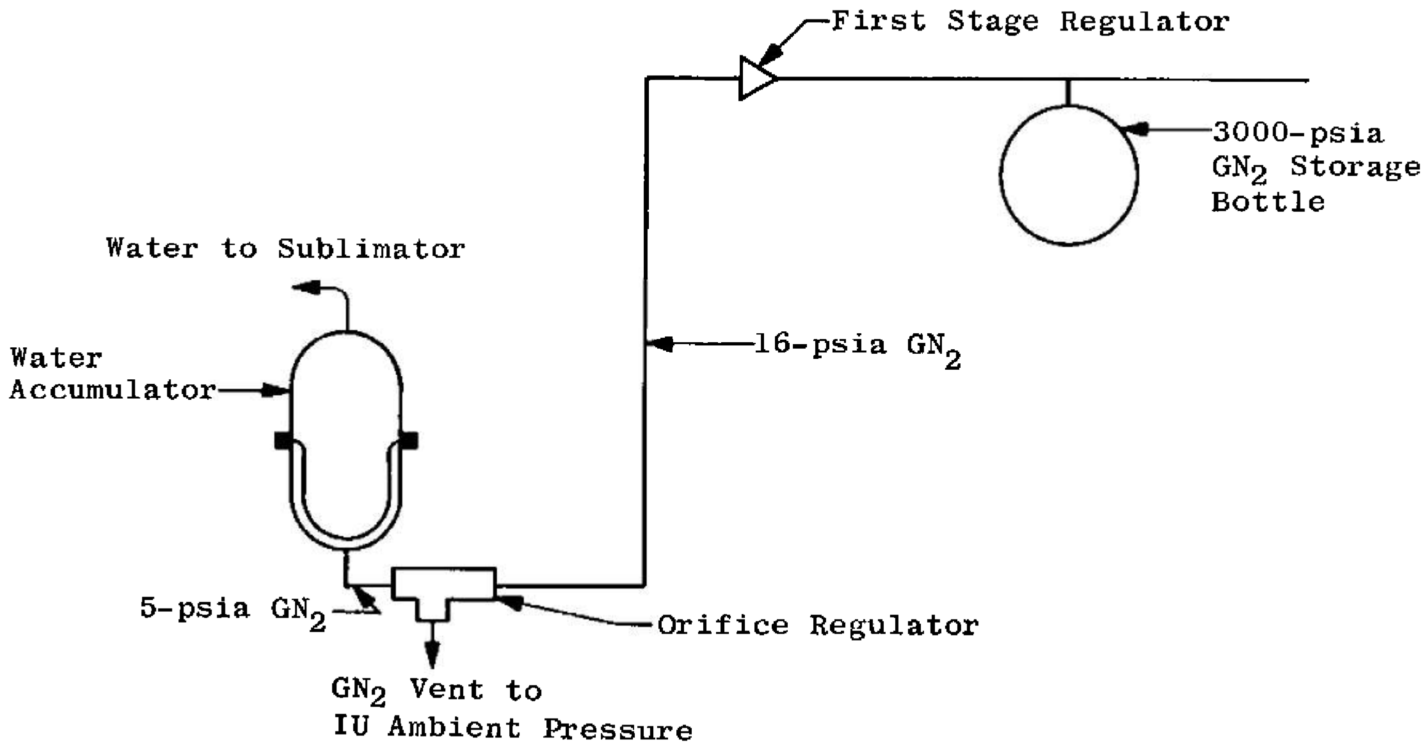


Fig. 14 Flight Pressurization Orifice Regulator Schematic

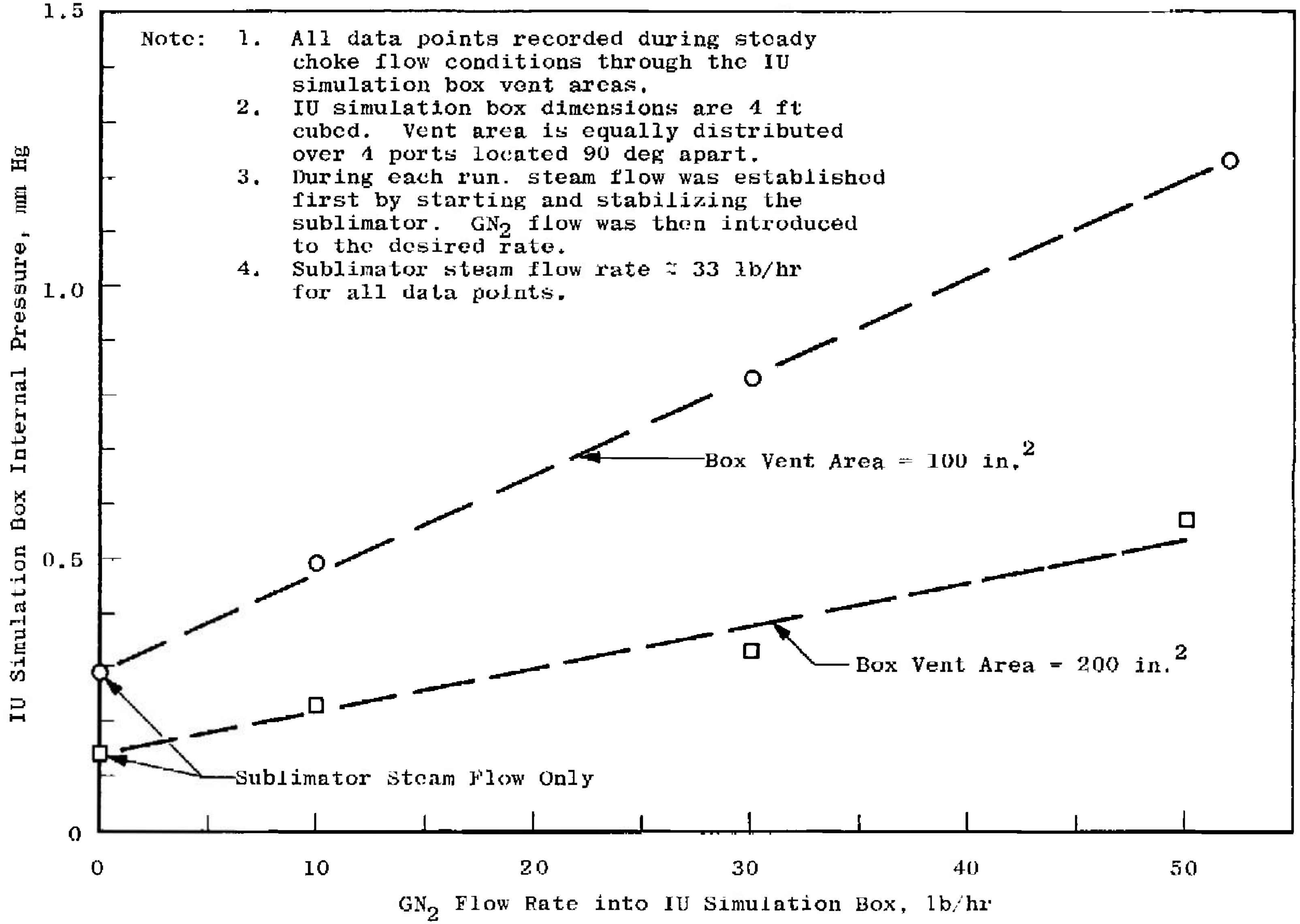


Fig. 15 Internal Pressure of IU Simulation Box versus GN_2 Flow Rates for Vent Areas of 200 and 100 in.^{2}

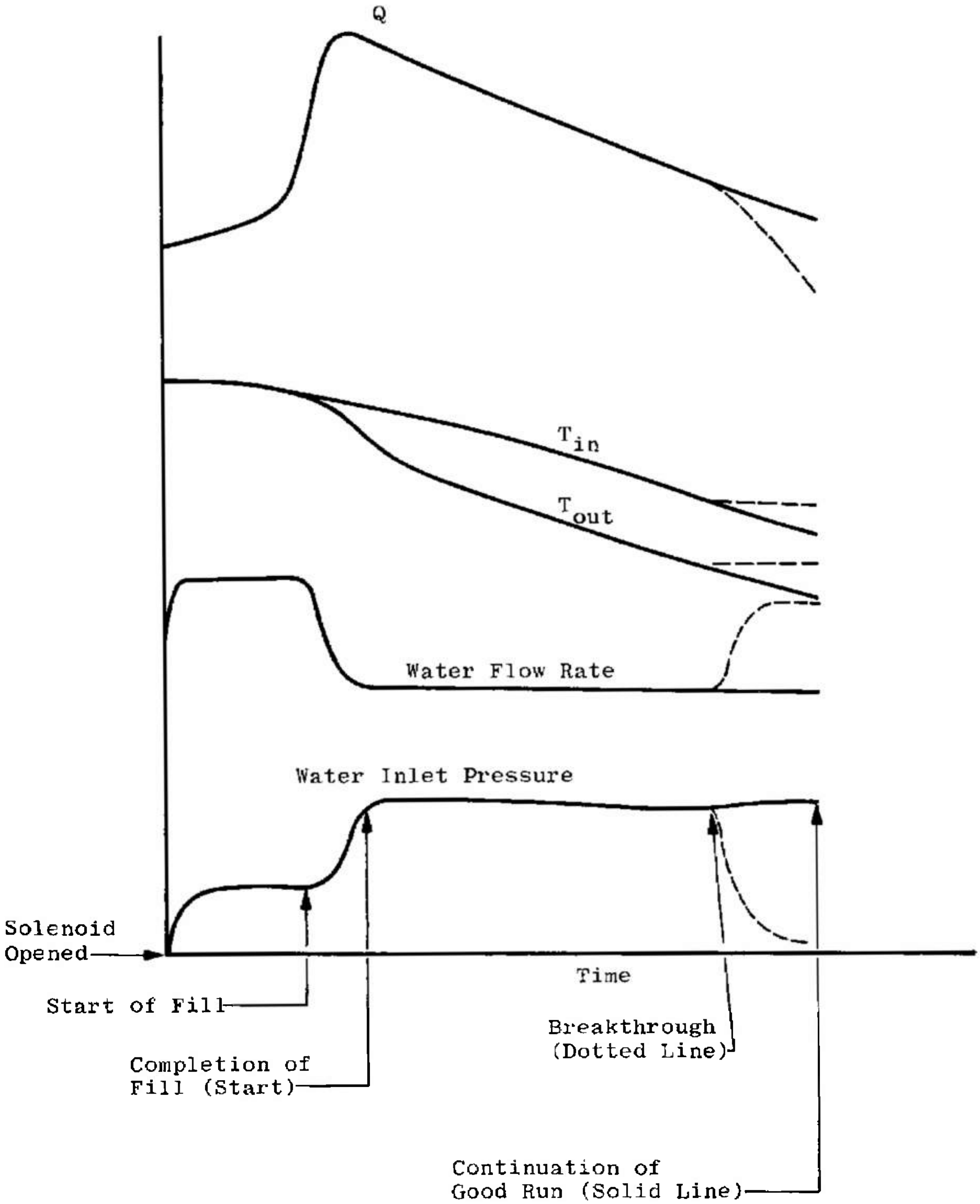


Fig. 16 Parameters Used to Indicate Sublimator Performance

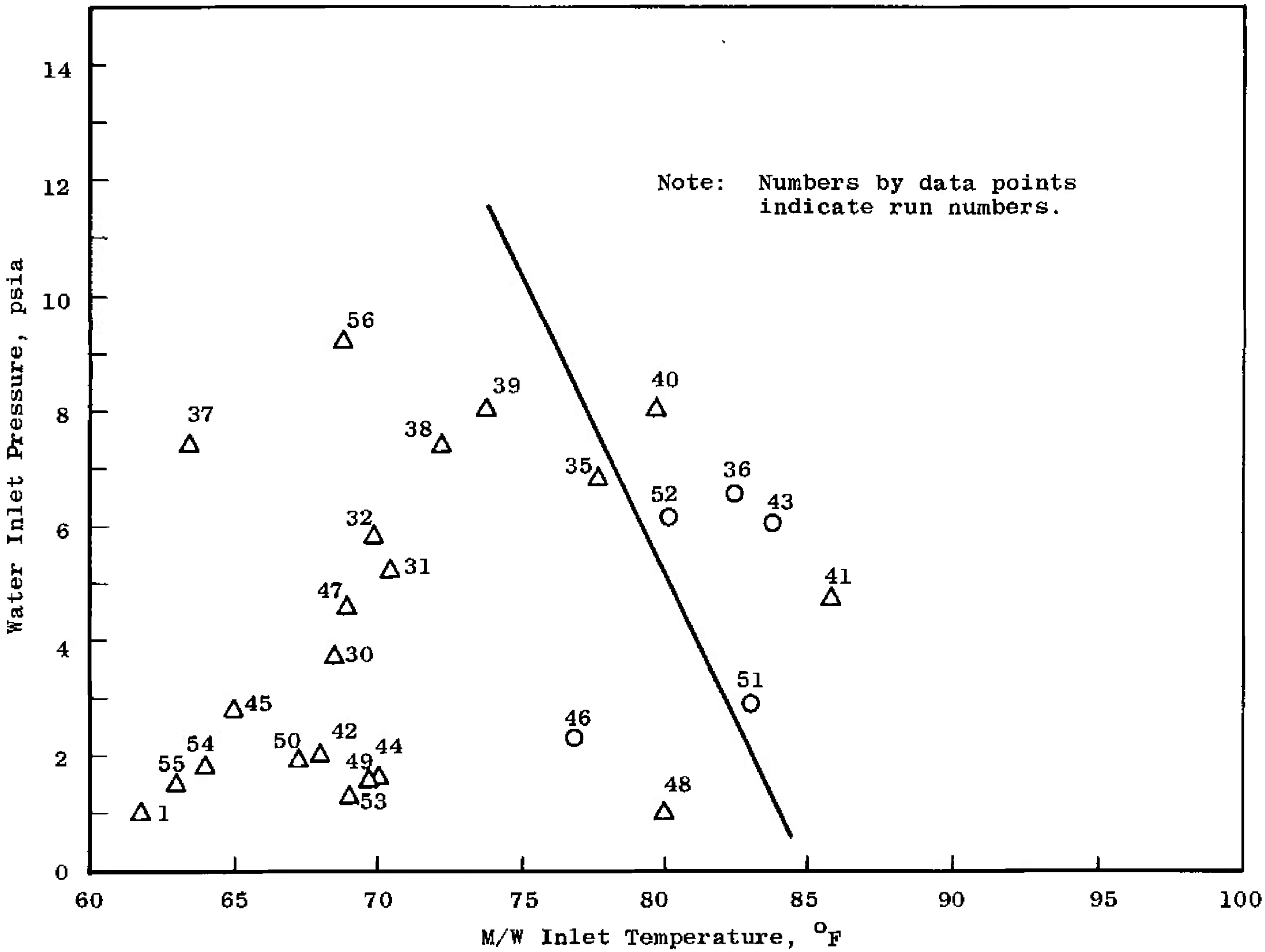


Fig. 17 Critical Starting Conditions Plot for SN 10 with Flowmeter

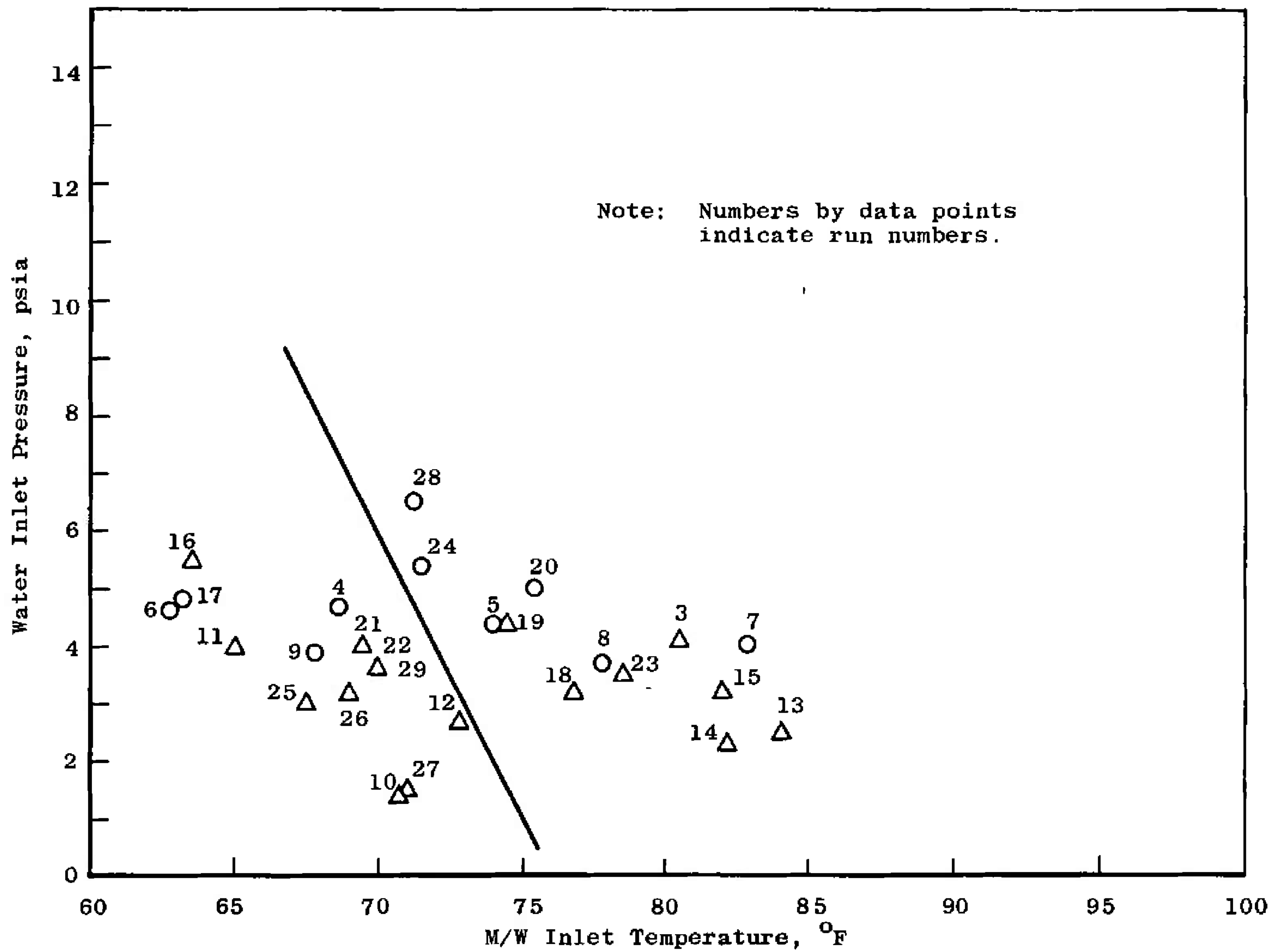


Fig. 18 Critical Starting Conditions Plot for SN10 without Flowmeter

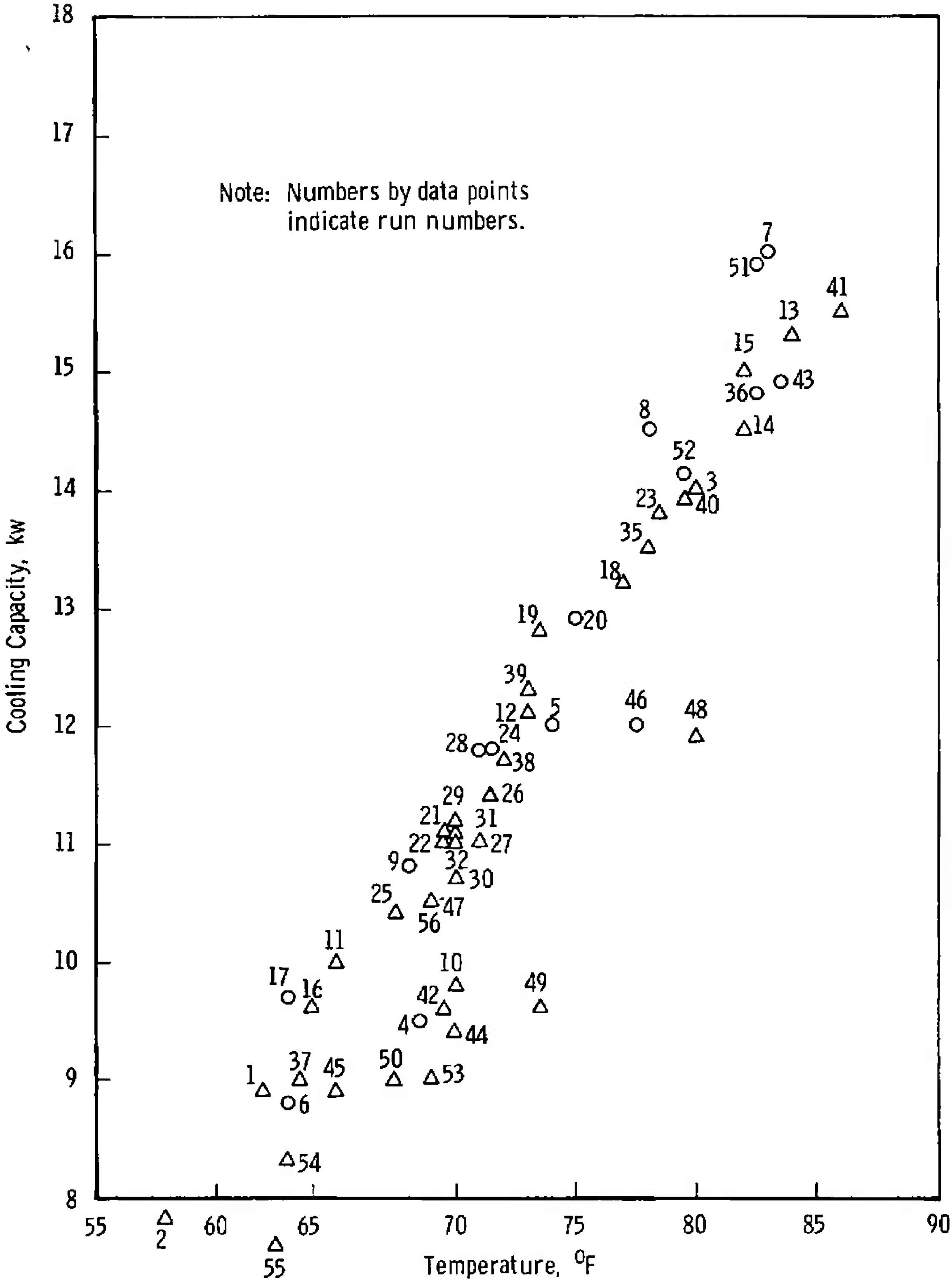


Fig. 19 Refrigeration Capacity Plot for SN10

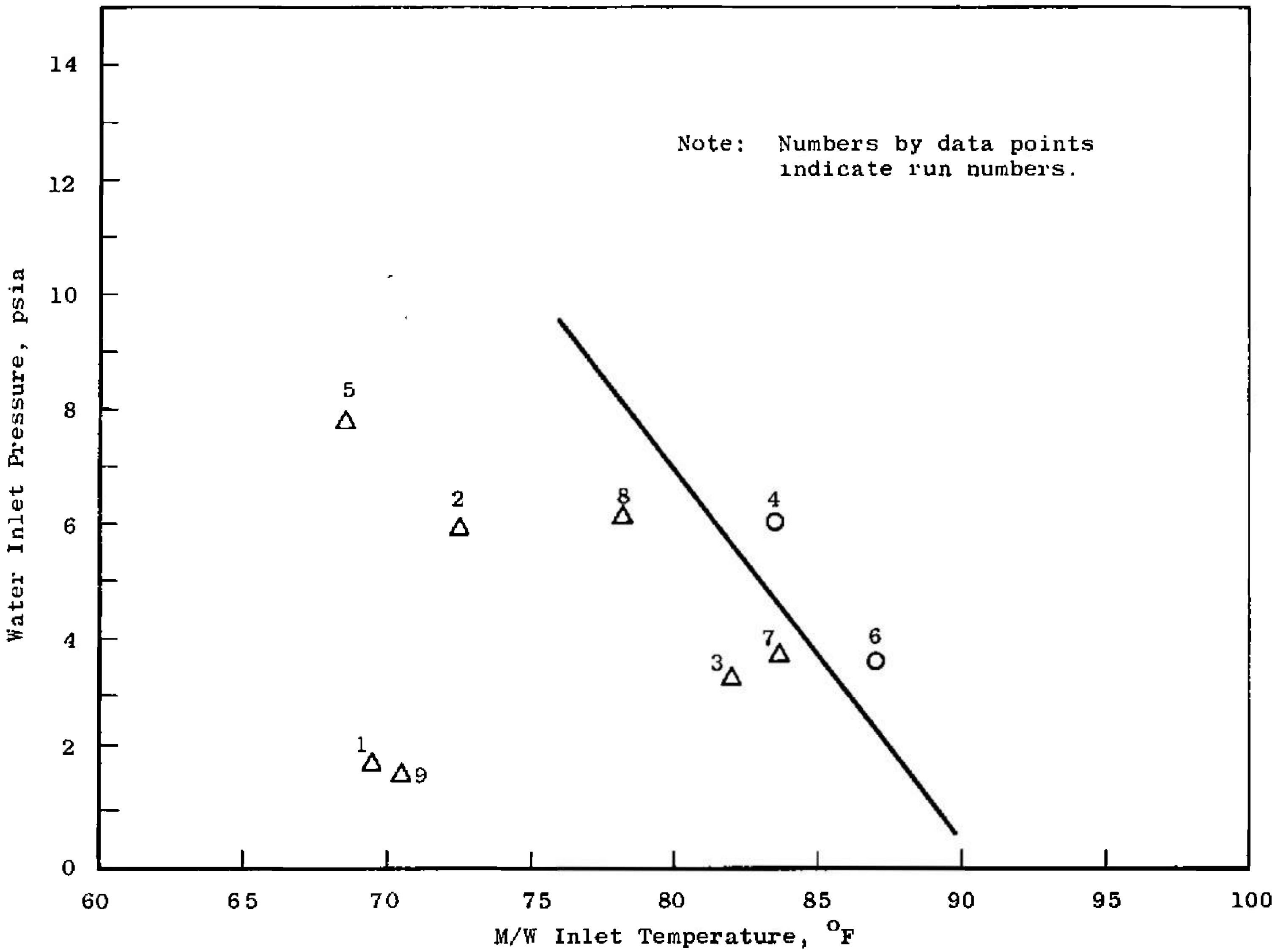


Fig. 20 Critical Starting Conditions Plot for SN9 with Flowmeter

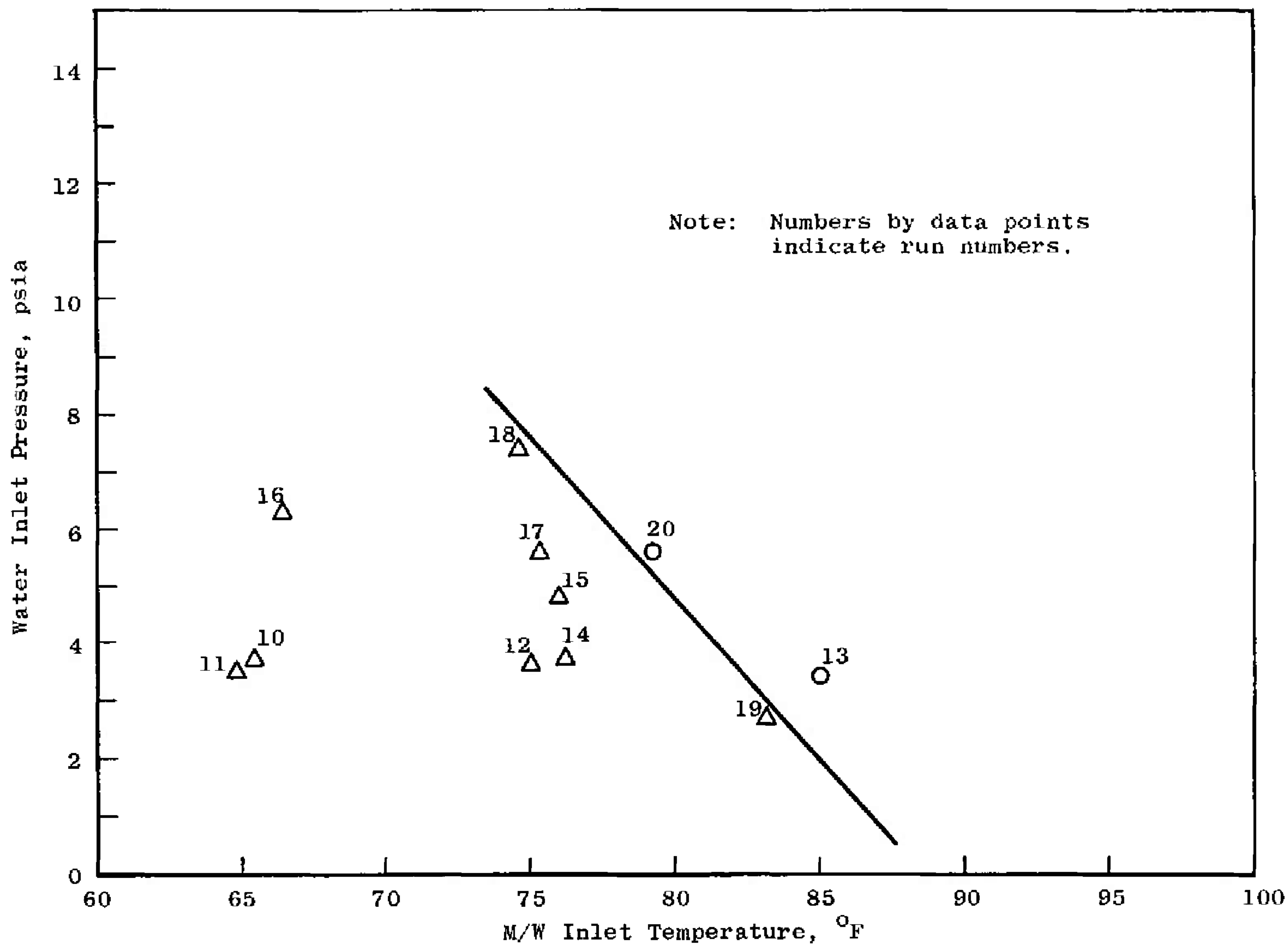


Fig. 21 Critical Starting Conditions Plot for SN9 without Flowmeter

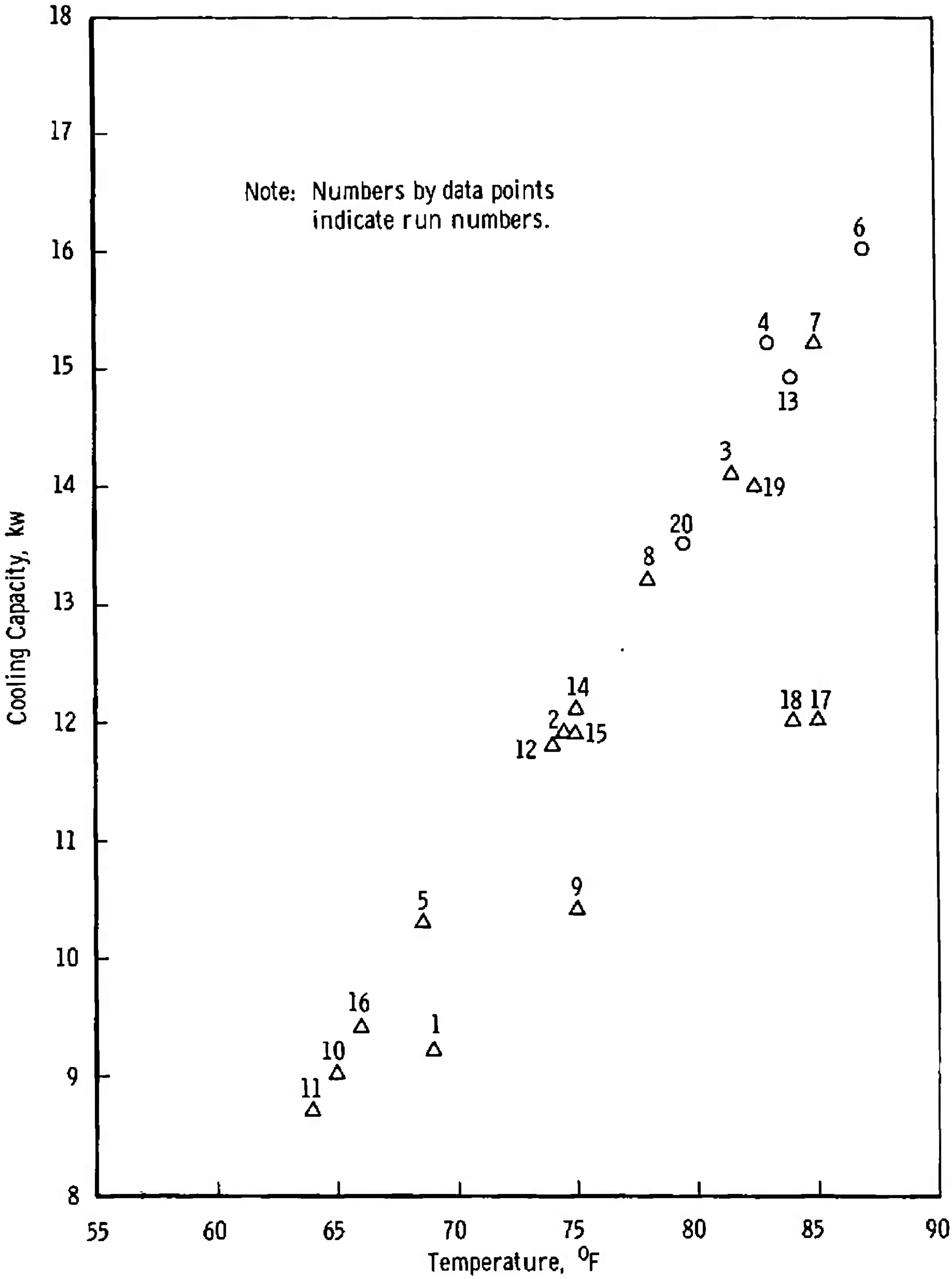


Fig. 22 Refrigeration Capacity Plot for SN9

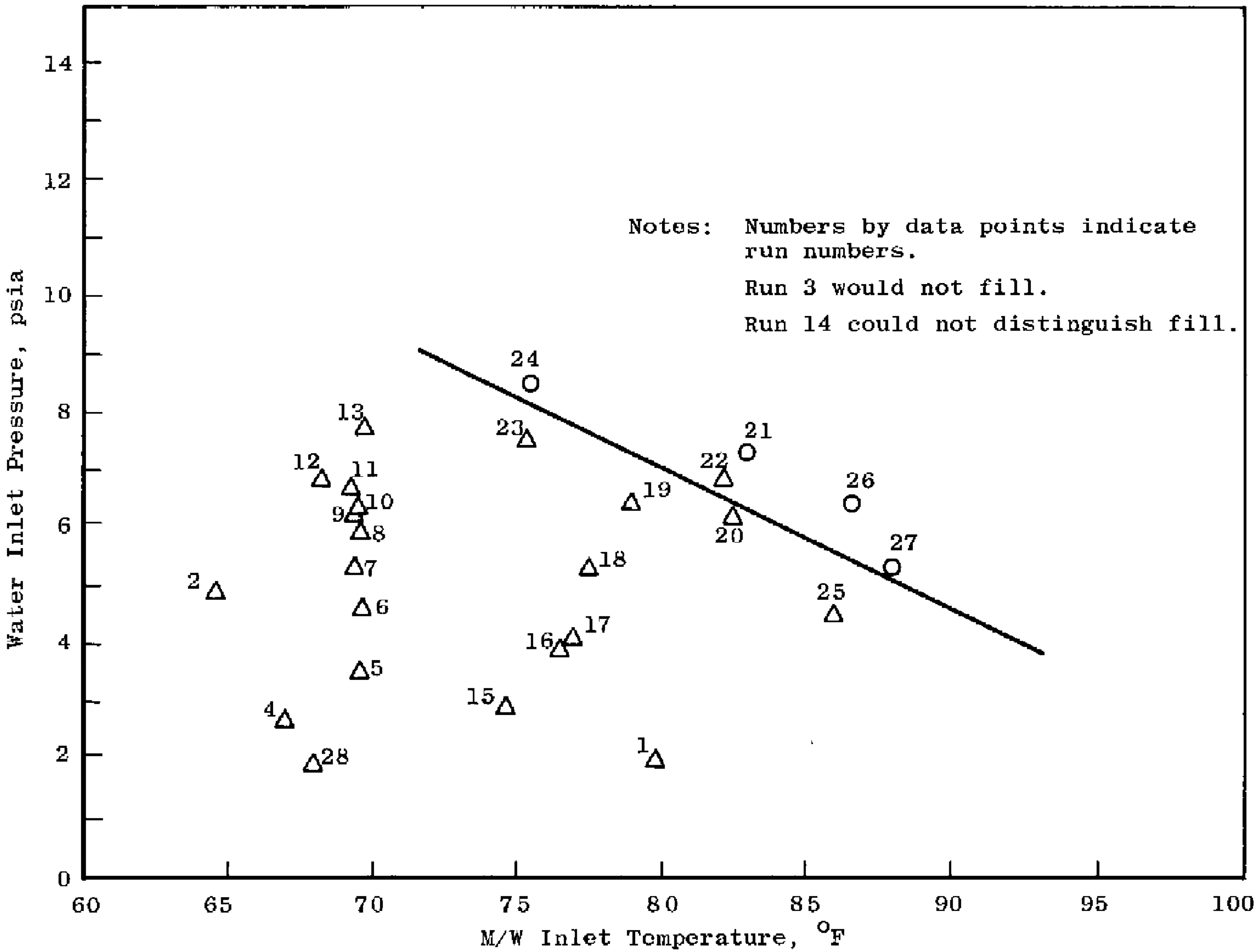


Fig. 23 Critical Starting Conditions Plot for SN4′(0.068-in. Orifice) with Flowmeter

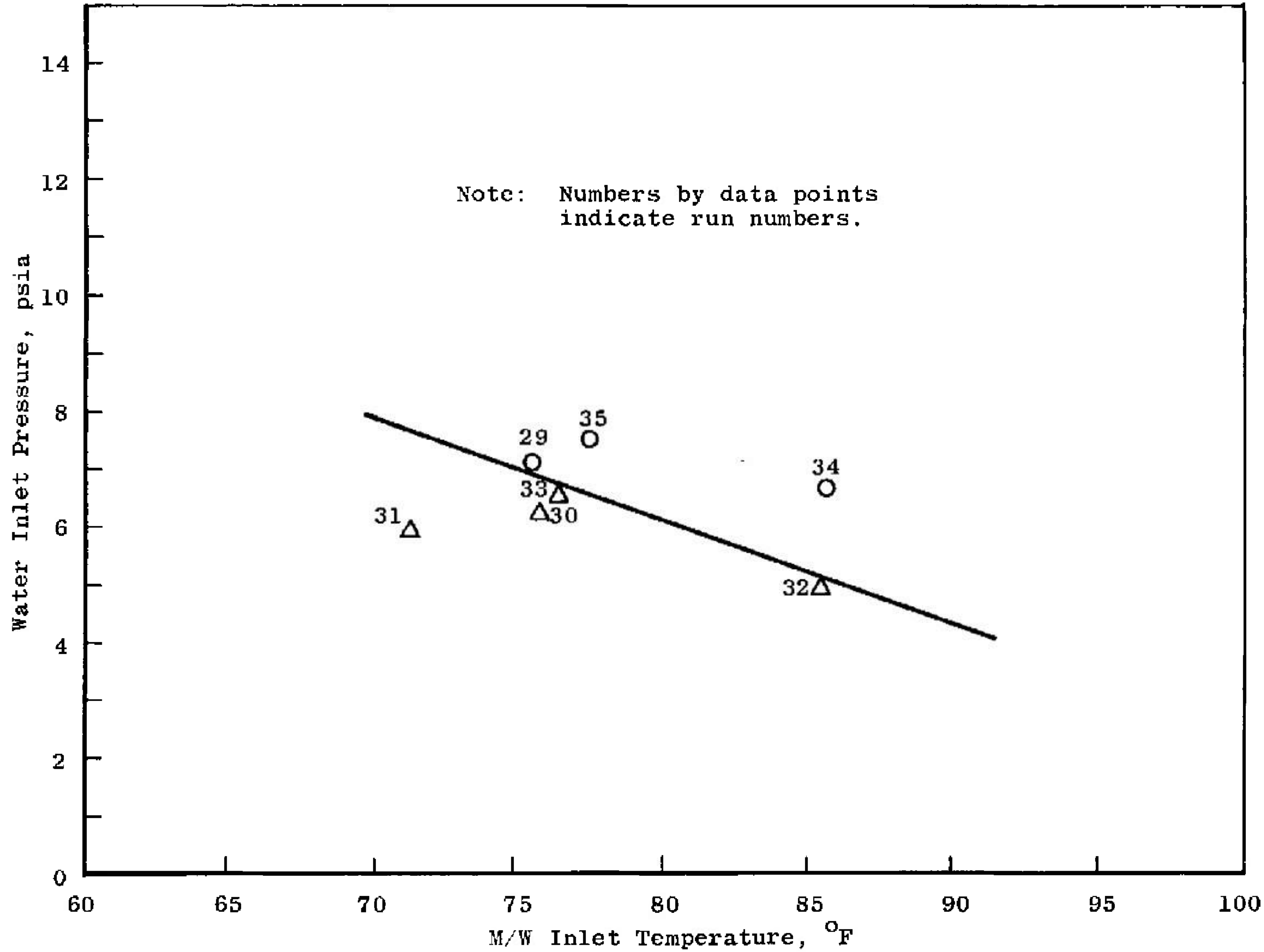


Fig. 24 Critical Starting Conditions Plot for SN4′ (0.068-in. Orifice) without Flowmeter

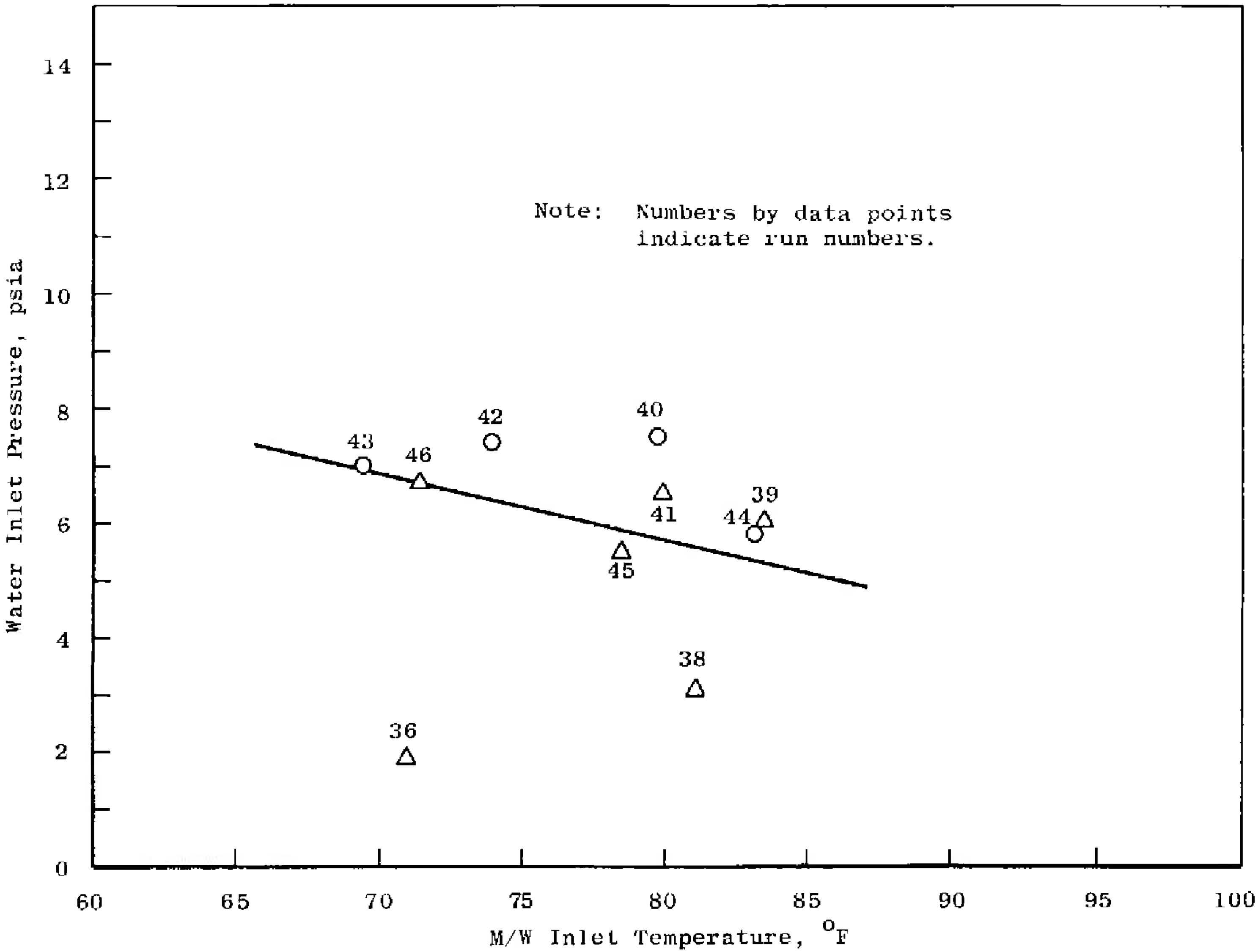


Fig. 25 Critical Starting Conditions Plot for SN4′ (0.068-in. Orifice) (Horizontal) with Flowmeter

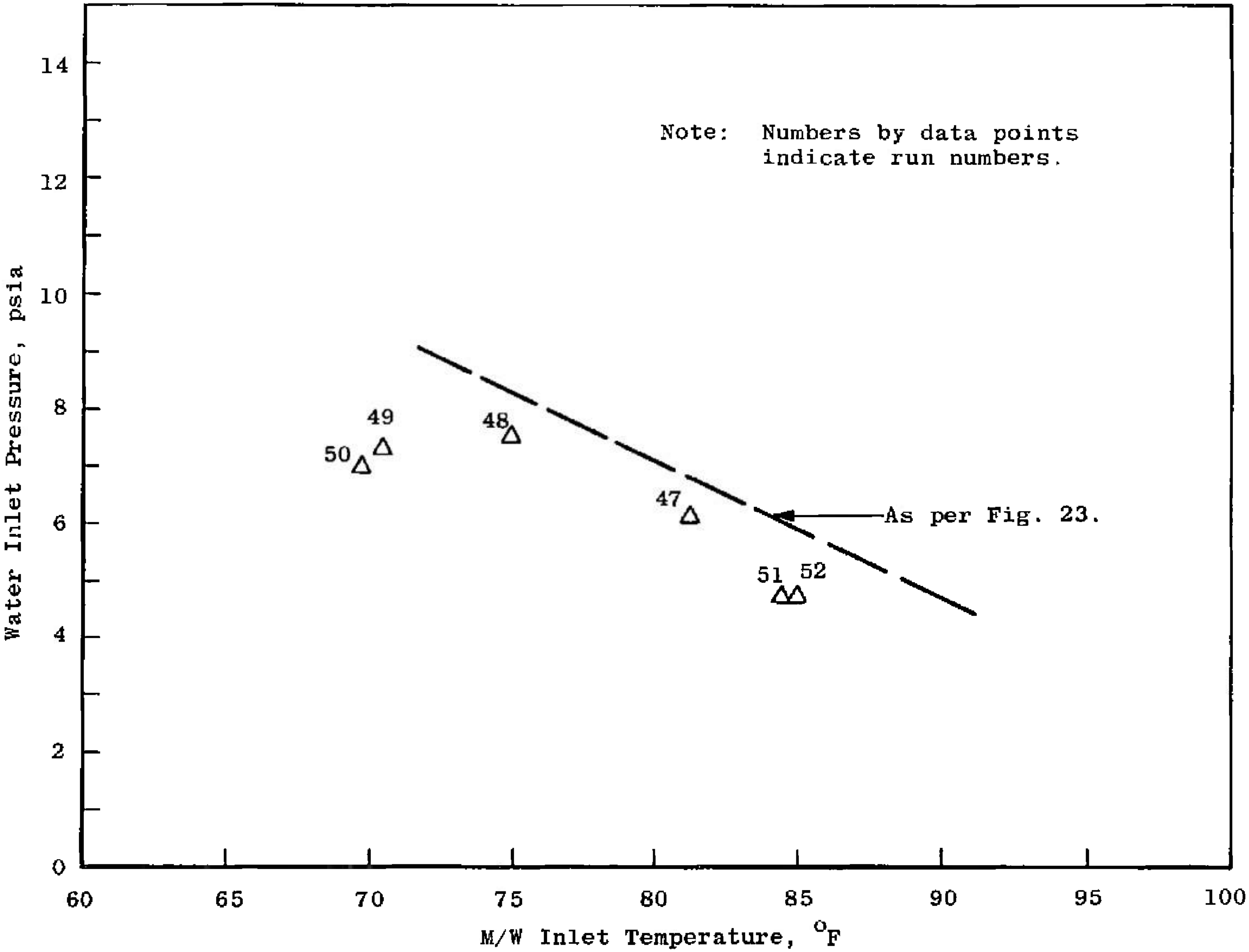


Fig. 26 Critical Starting Conditions Plot for SN4′ (0.068-in. Orifice) without Flowmeter

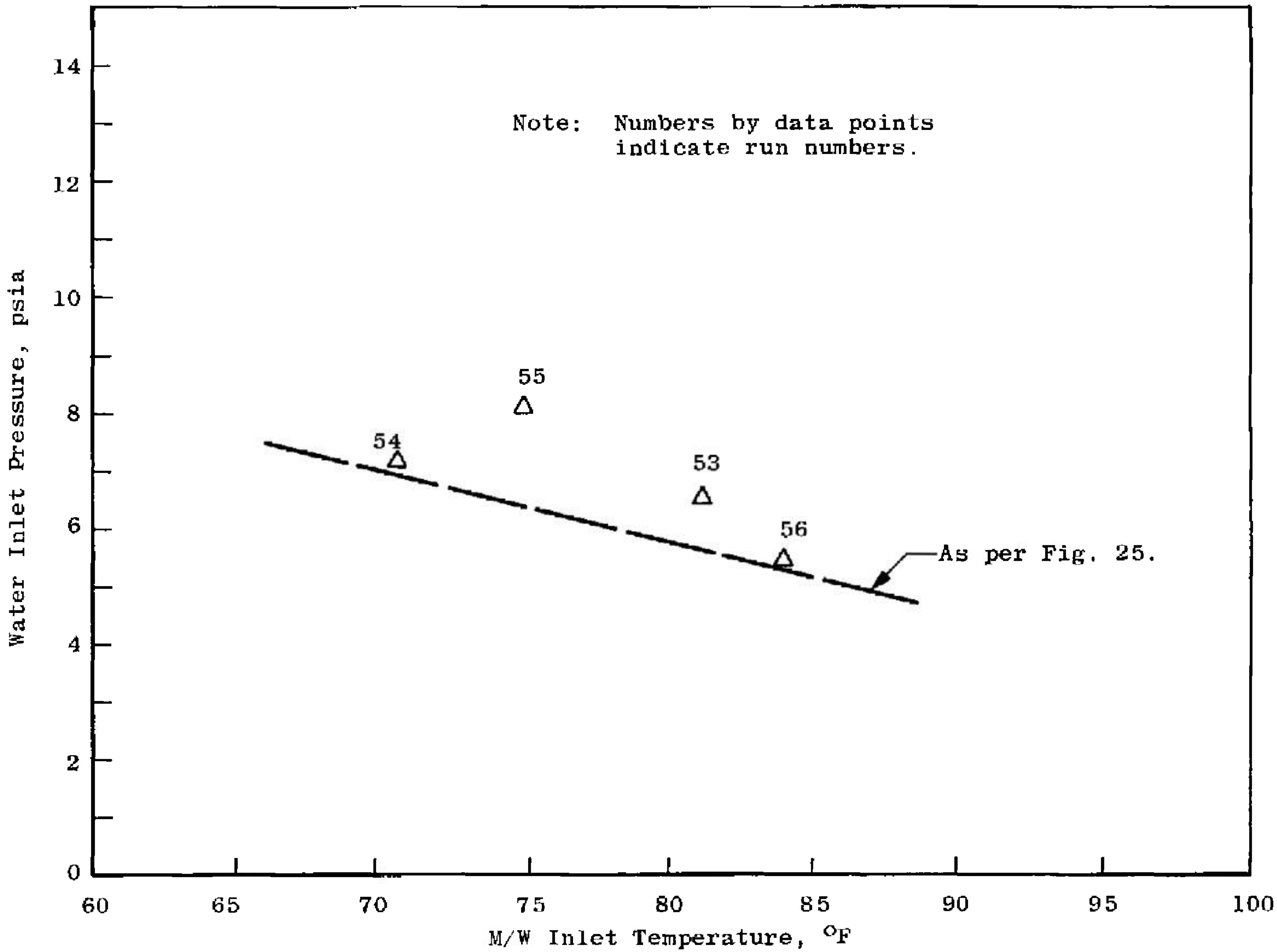


Fig. 27 Critical Starting Conditions Plot for SN4′ (0.068-in. Orifice) (Horizontal) with Flowmeter

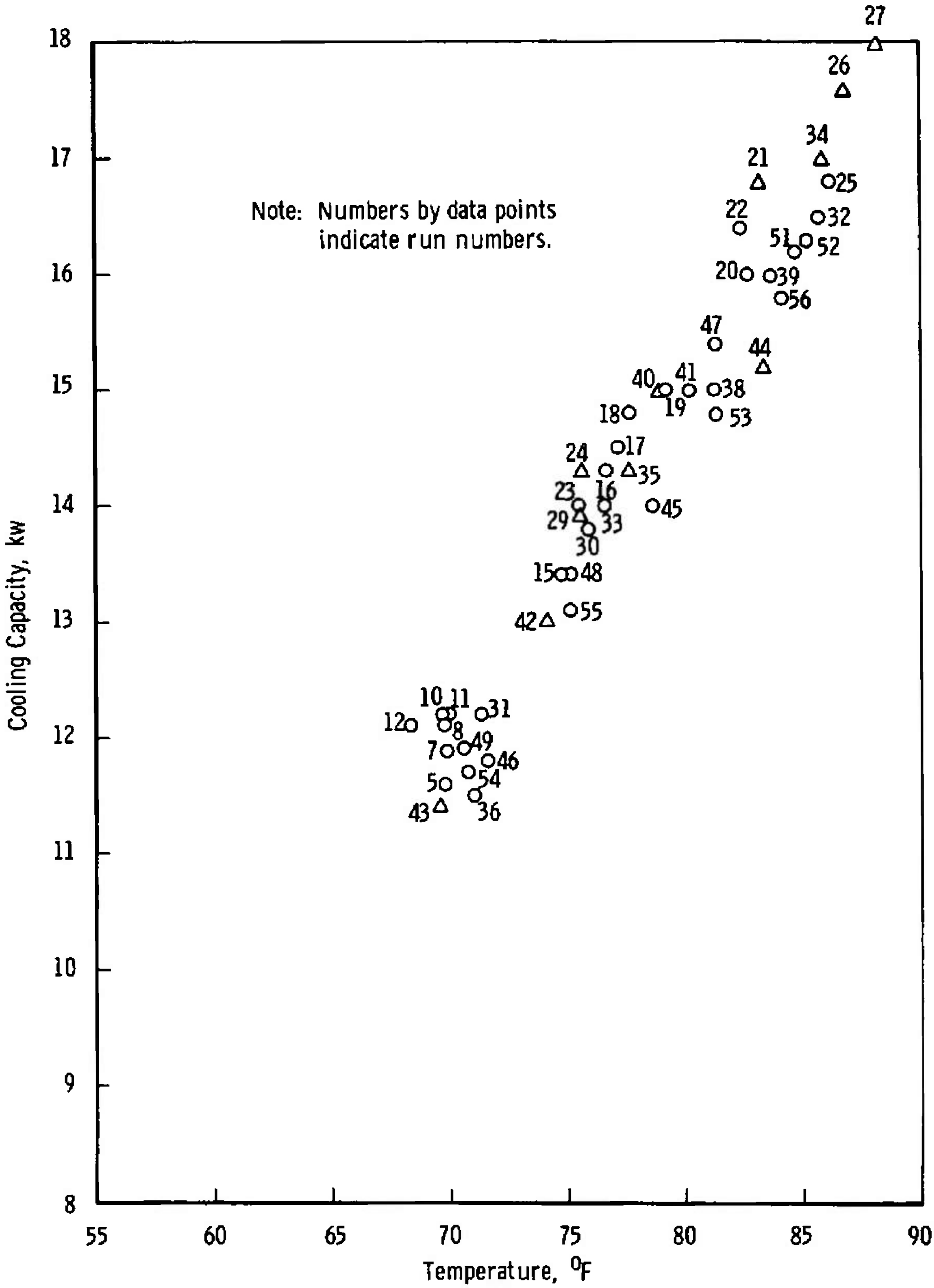


Fig. 28 Refrigeration Capacity Plot for SN4′(0.068-in.)

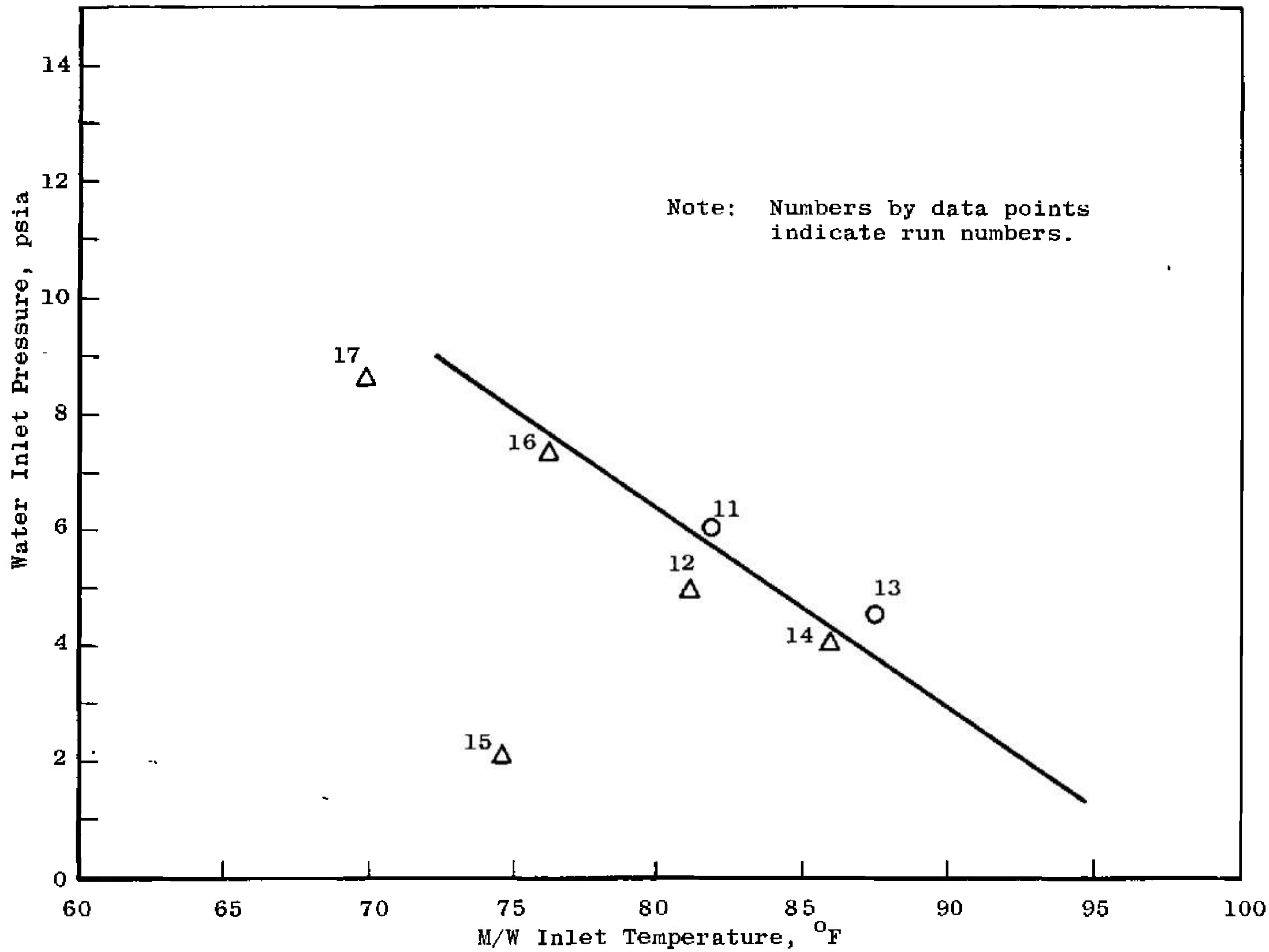


Fig. 29 Critical Starting Conditions Plot for SN4' (0.078-in. Orifice) with Flowmeter

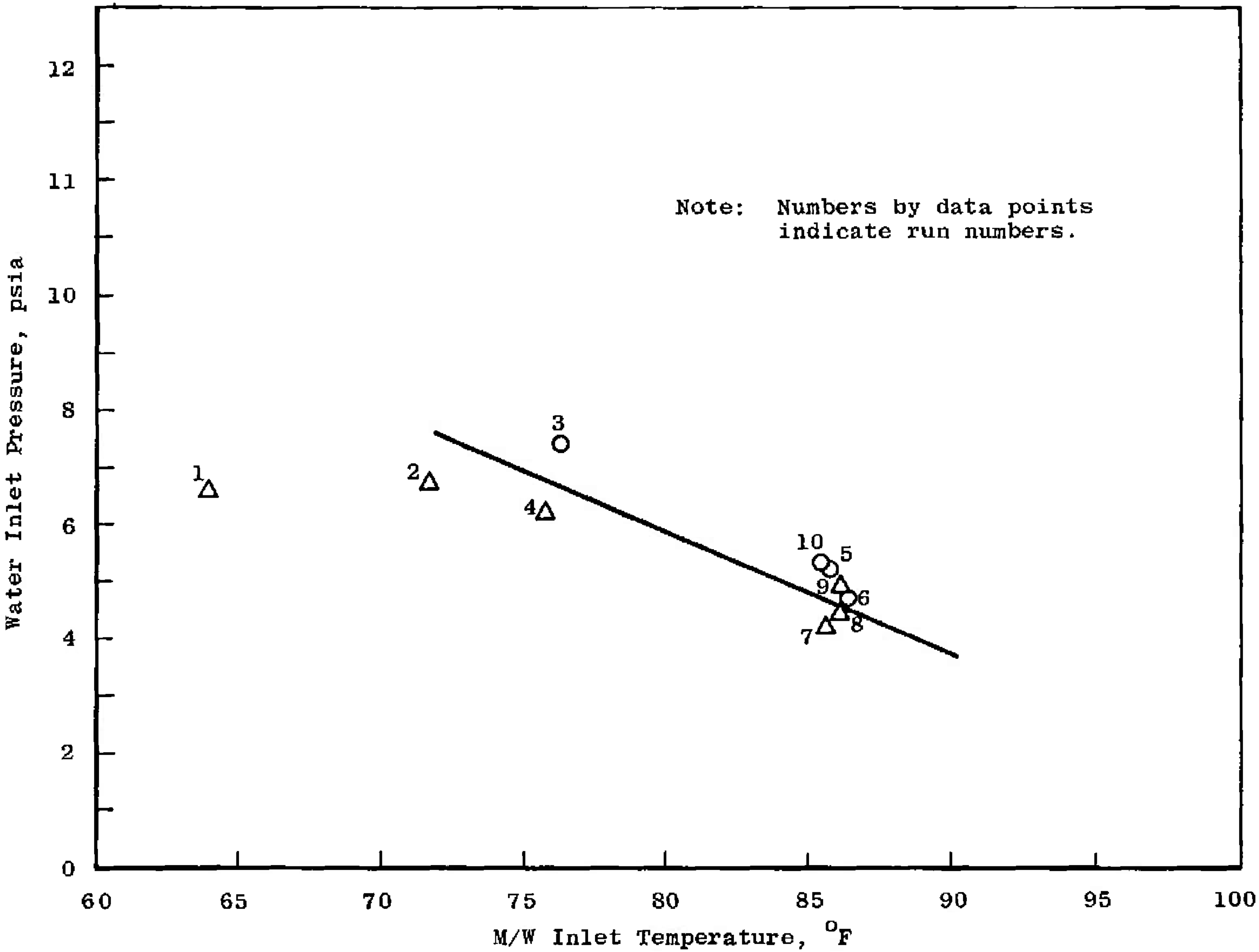


Fig. 30 Critical Starting Conditions Plot for SN4' (0.078-in. Orifice) without Flowmeter

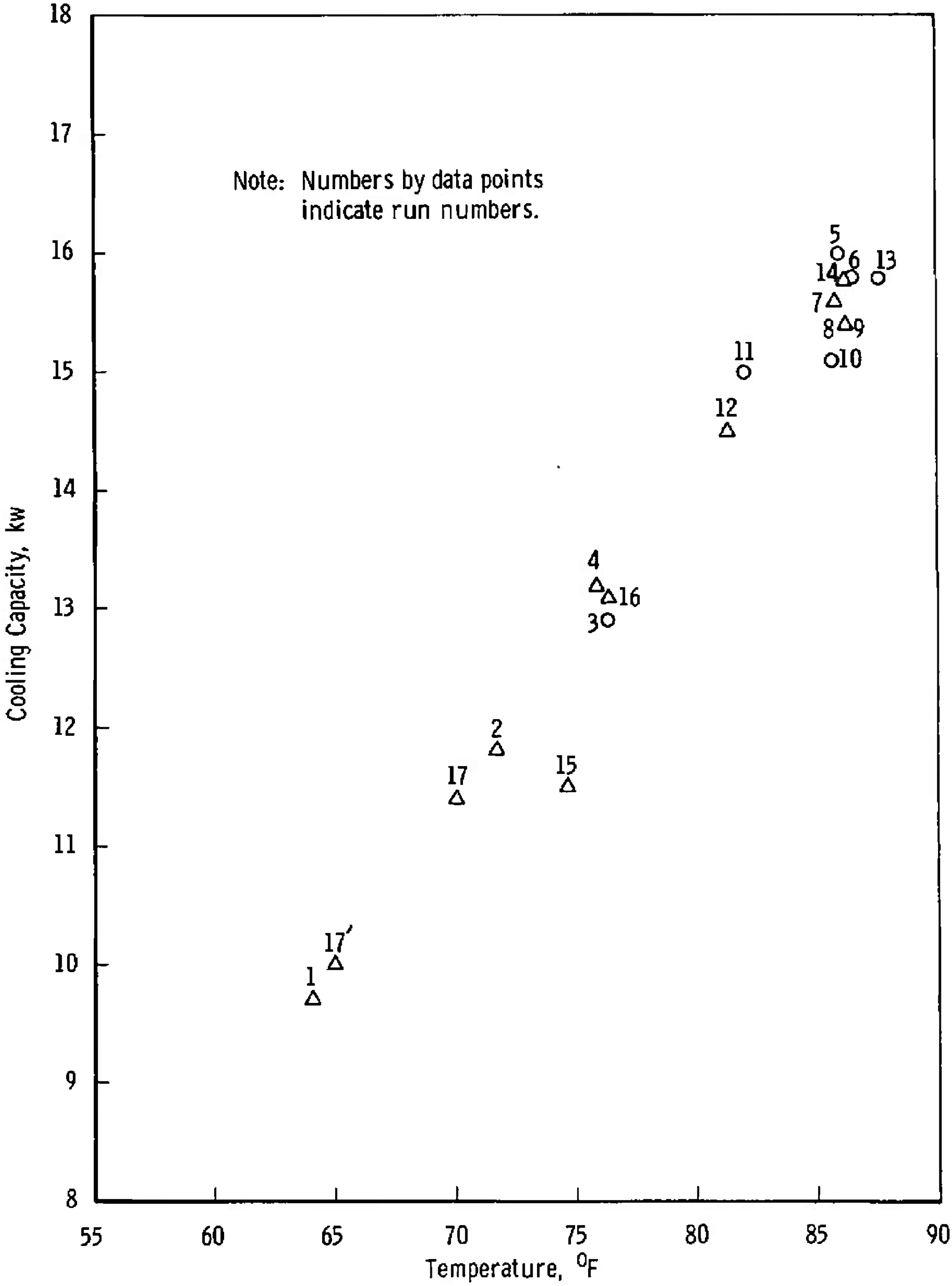


Fig. 31 Refrigeration Capacity Plot for SN4′(0.078-in.)

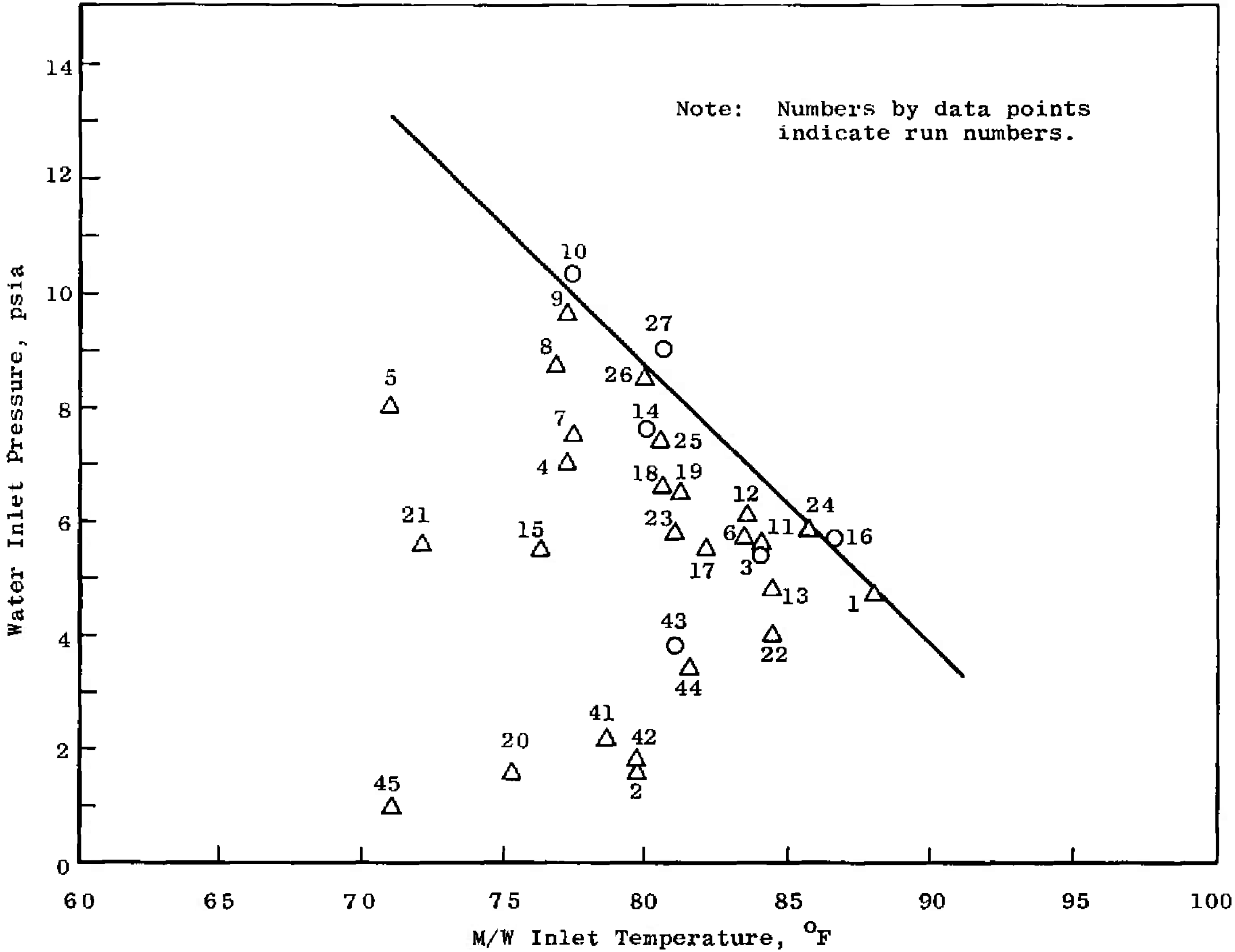


Fig. 32 Critical Starting Conditions Plot for SN3′ with Flowmeter

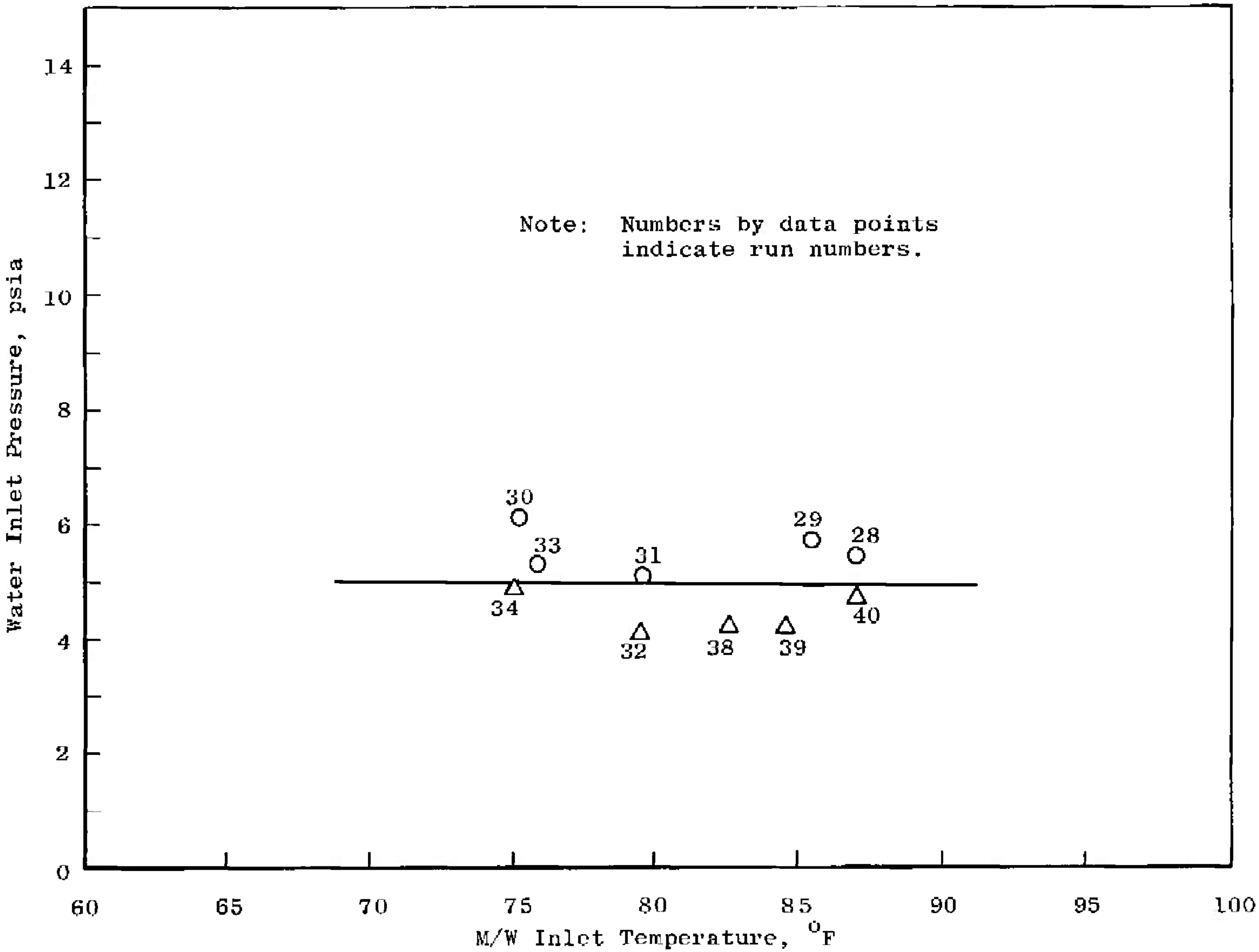


Fig. 33 Critical Starting Conditions Plot for SN3´without Flowmeter

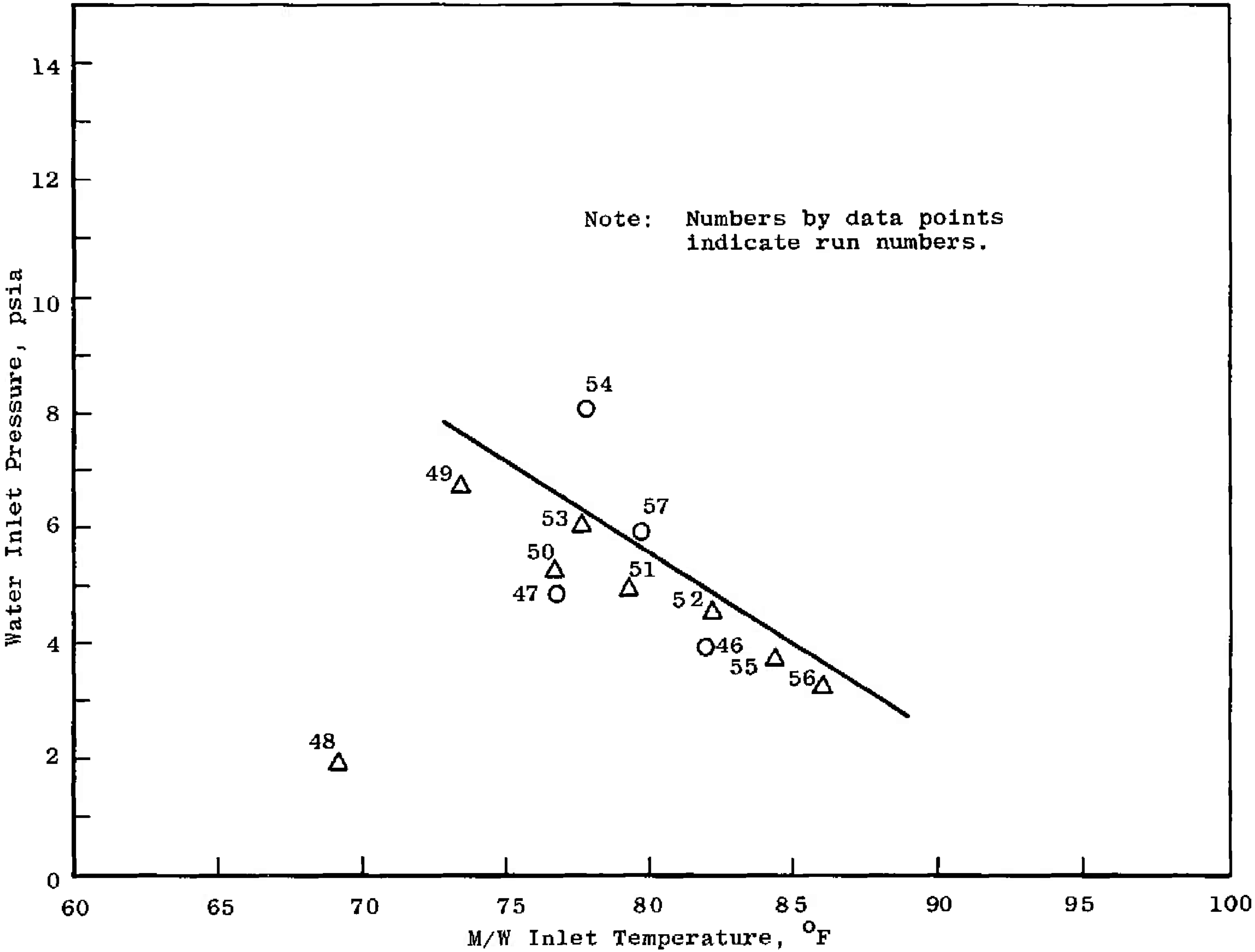


Fig. 34 Critical Starting Conditions Plot for SN3' (Horizontal) with Flowmeter

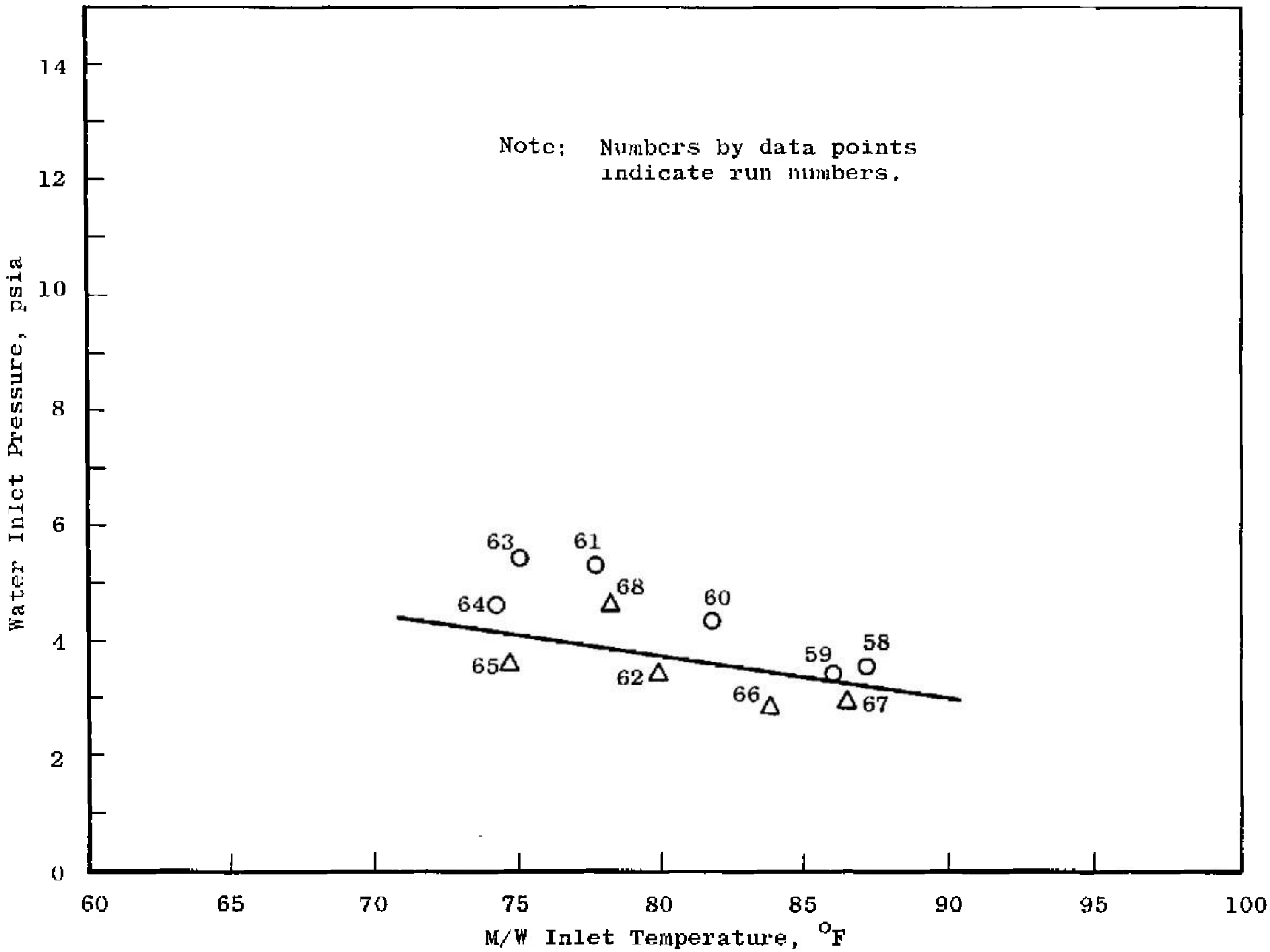


Fig. 35 Critical Starting Conditions Plot for SN3′ (Horizontal) without Flowmeter

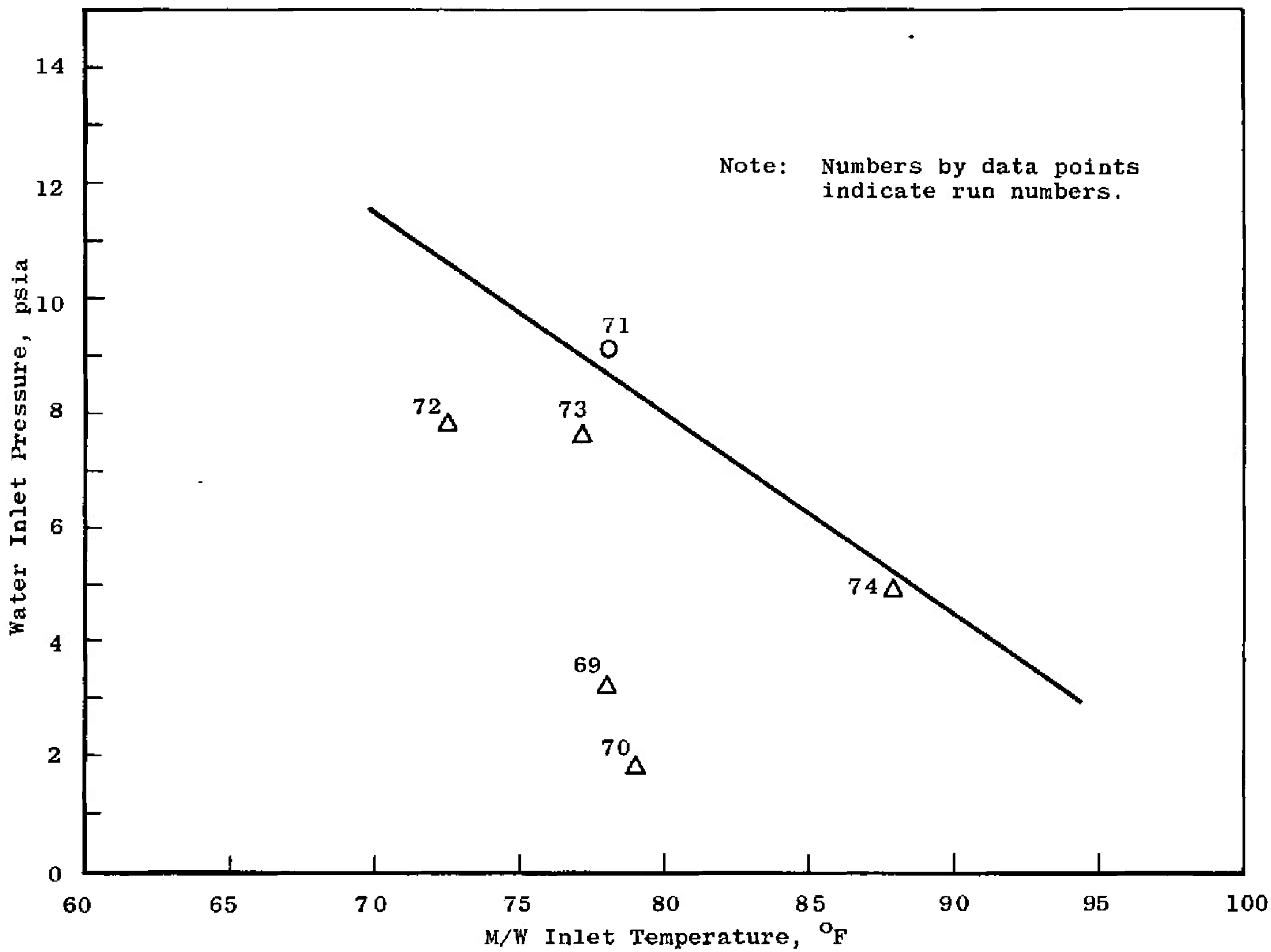


Fig. 36 Critical Starting Conditions Plot for SN3′ with Flowmeter

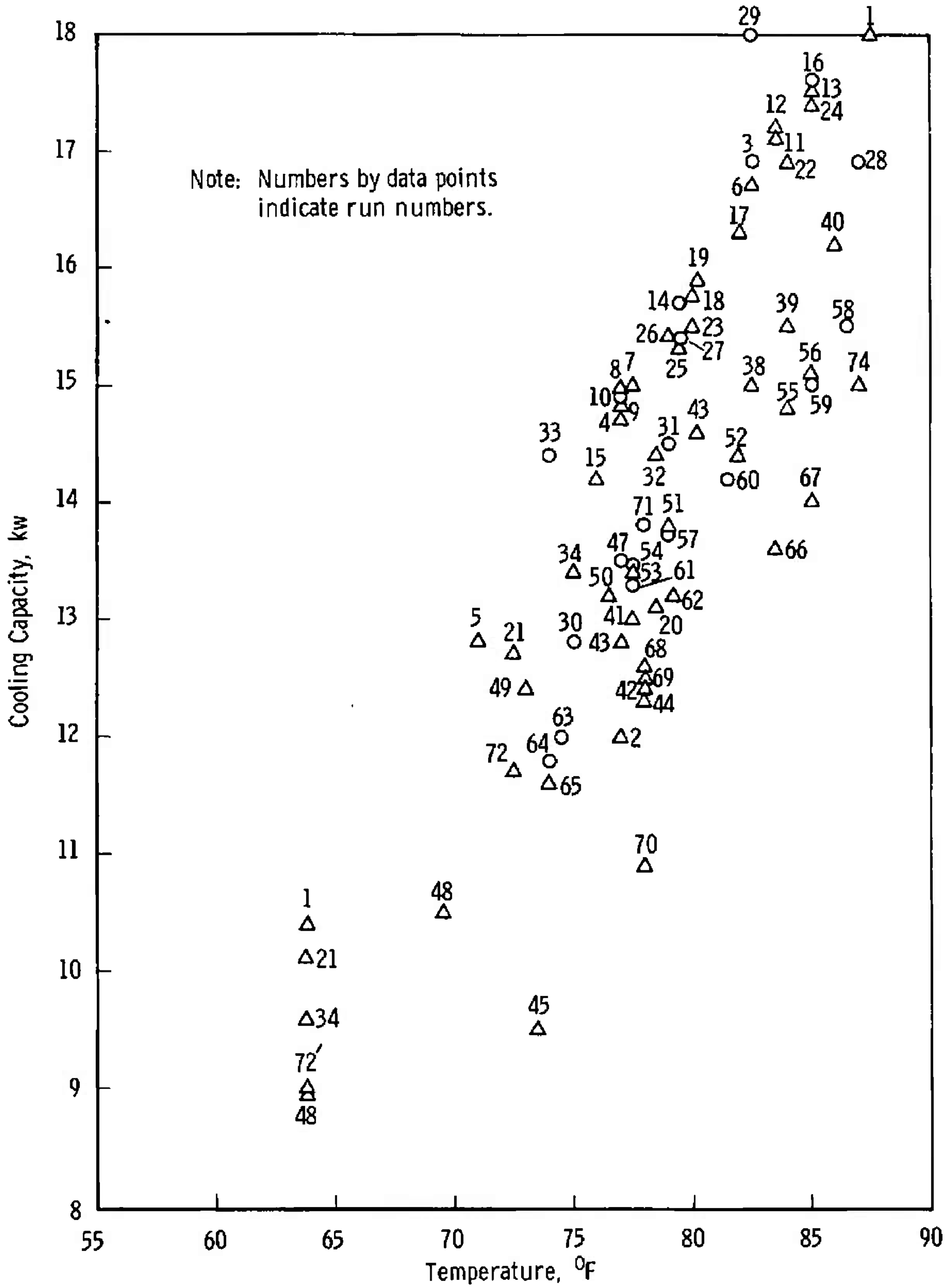


Fig. 37 Refrigeration Capacity Plot for SN3'

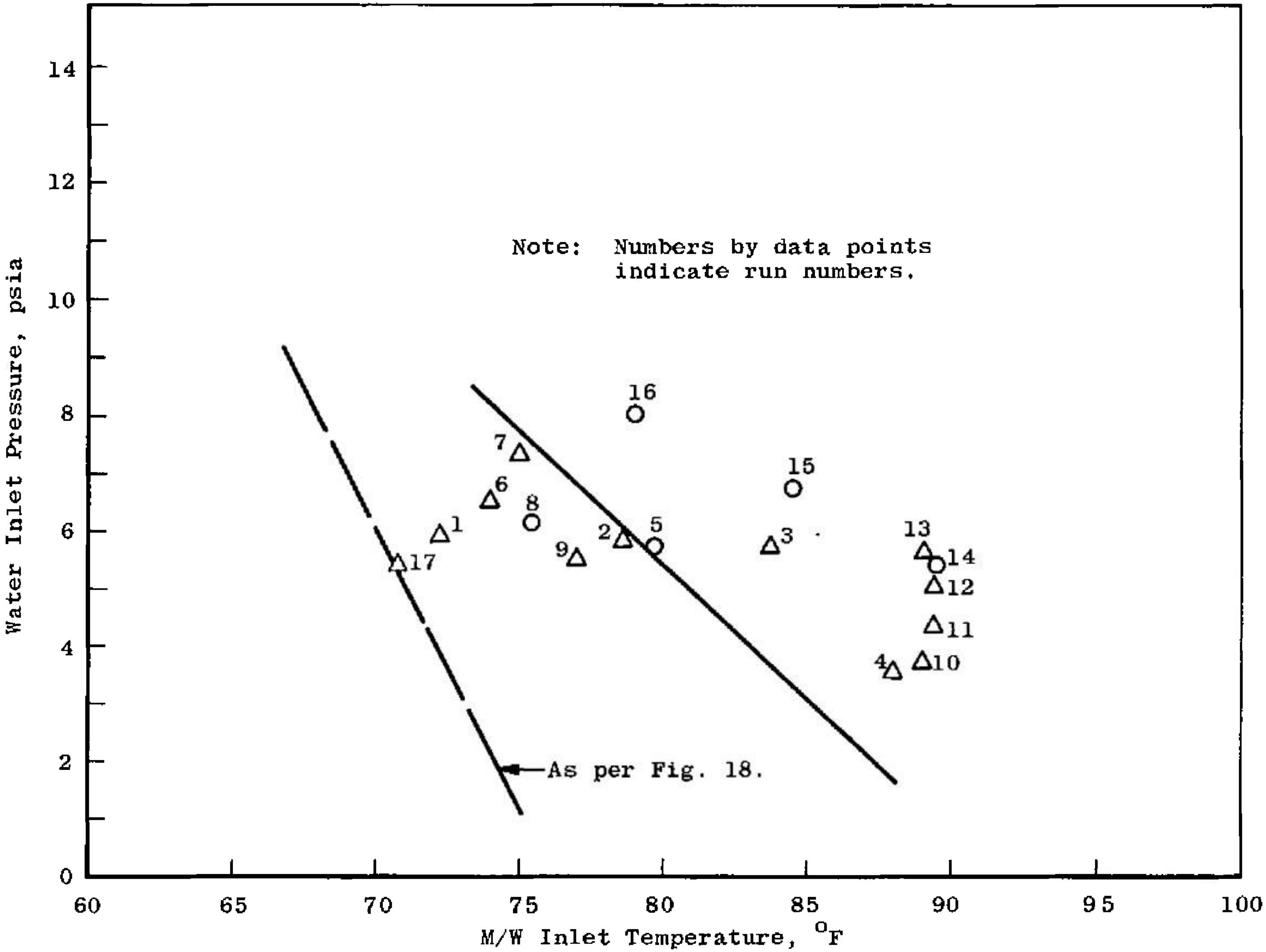


Fig. 38 Critical Starting Conditions Plot for SN10′ (Rerun) without Flowmeter

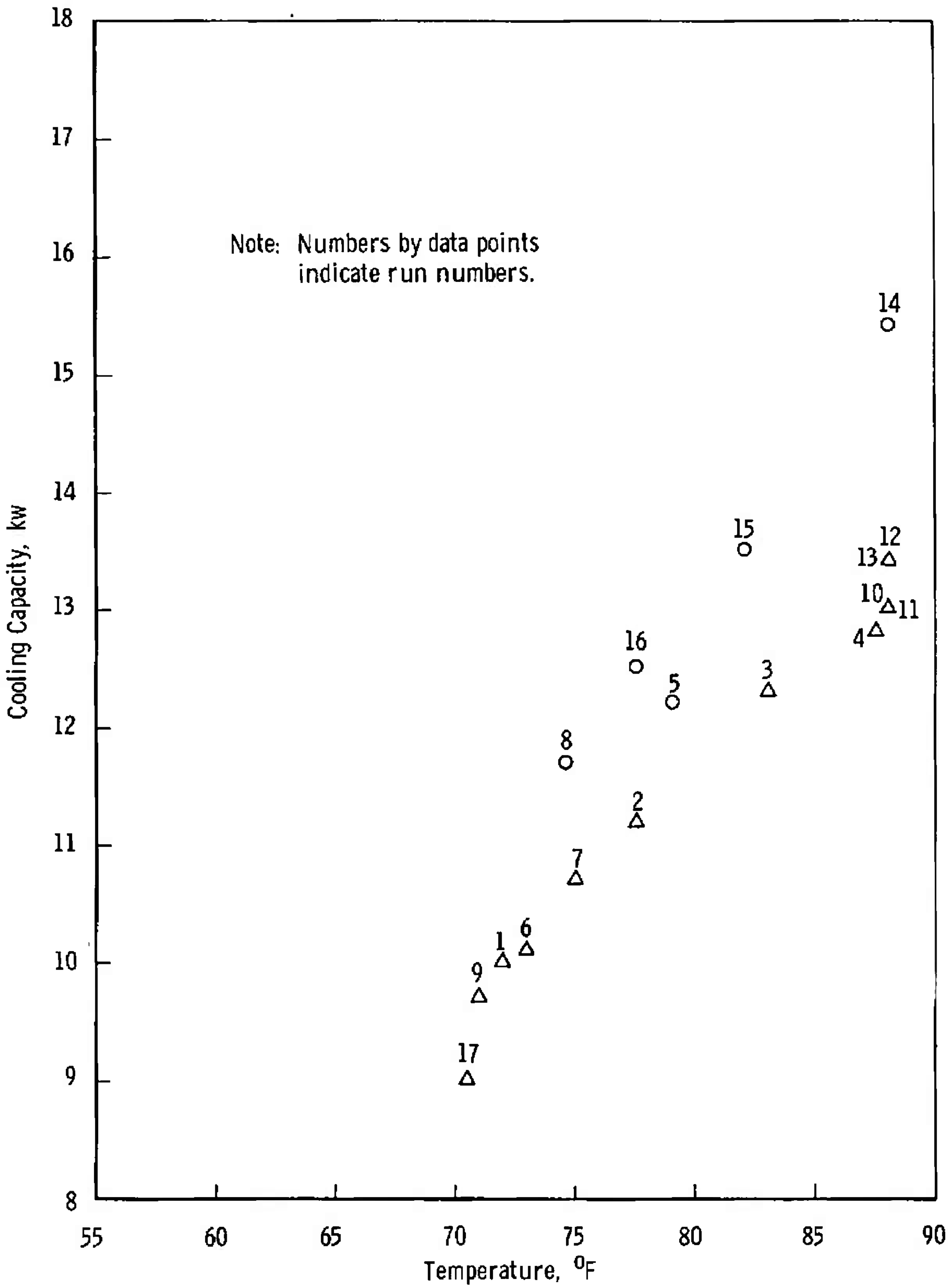


Fig. 39 Refrigeration Capacity Plot for SN10 (Rerun)

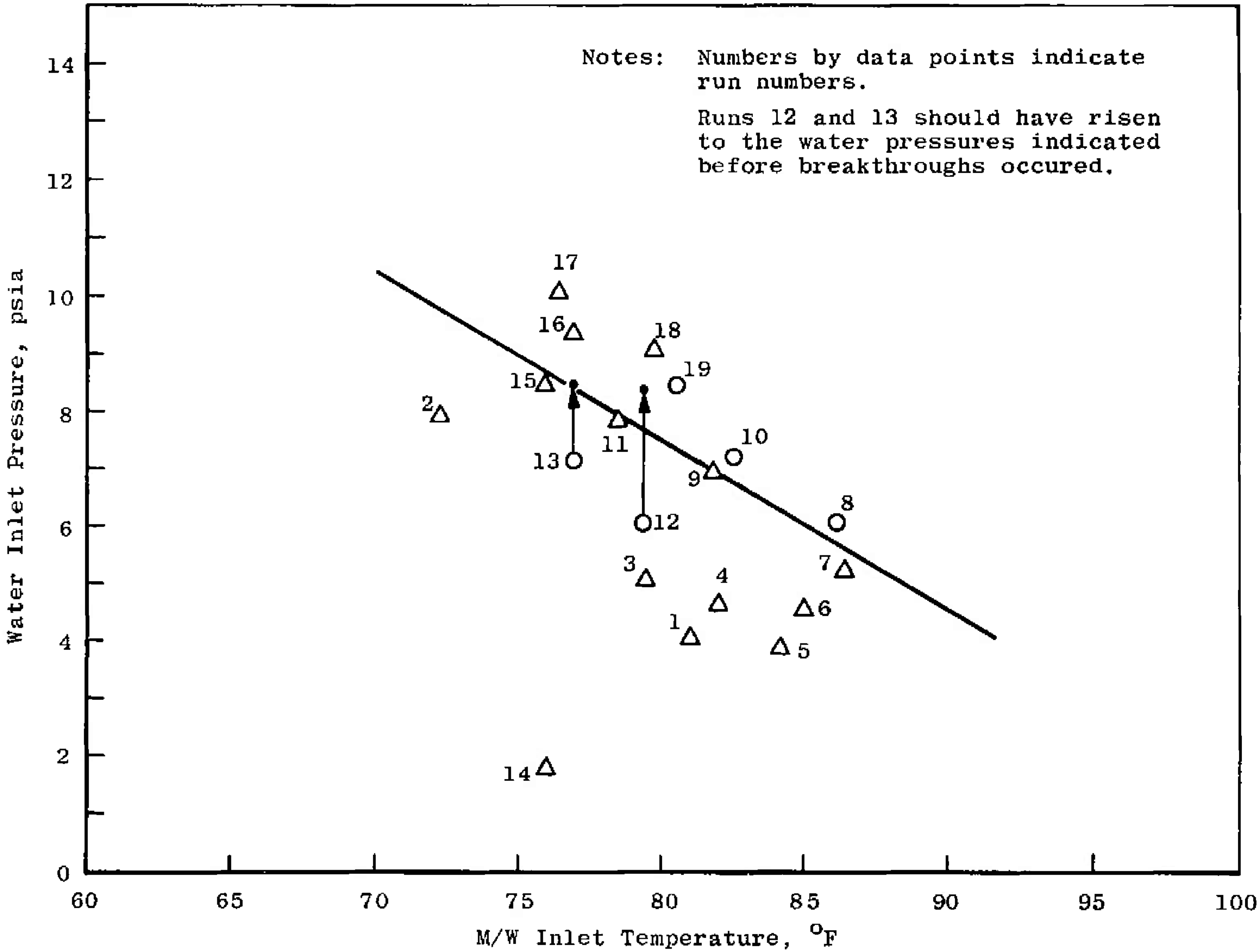


Fig. 40 Critical Starting Conditions Plot for SN5' with Flowmeter

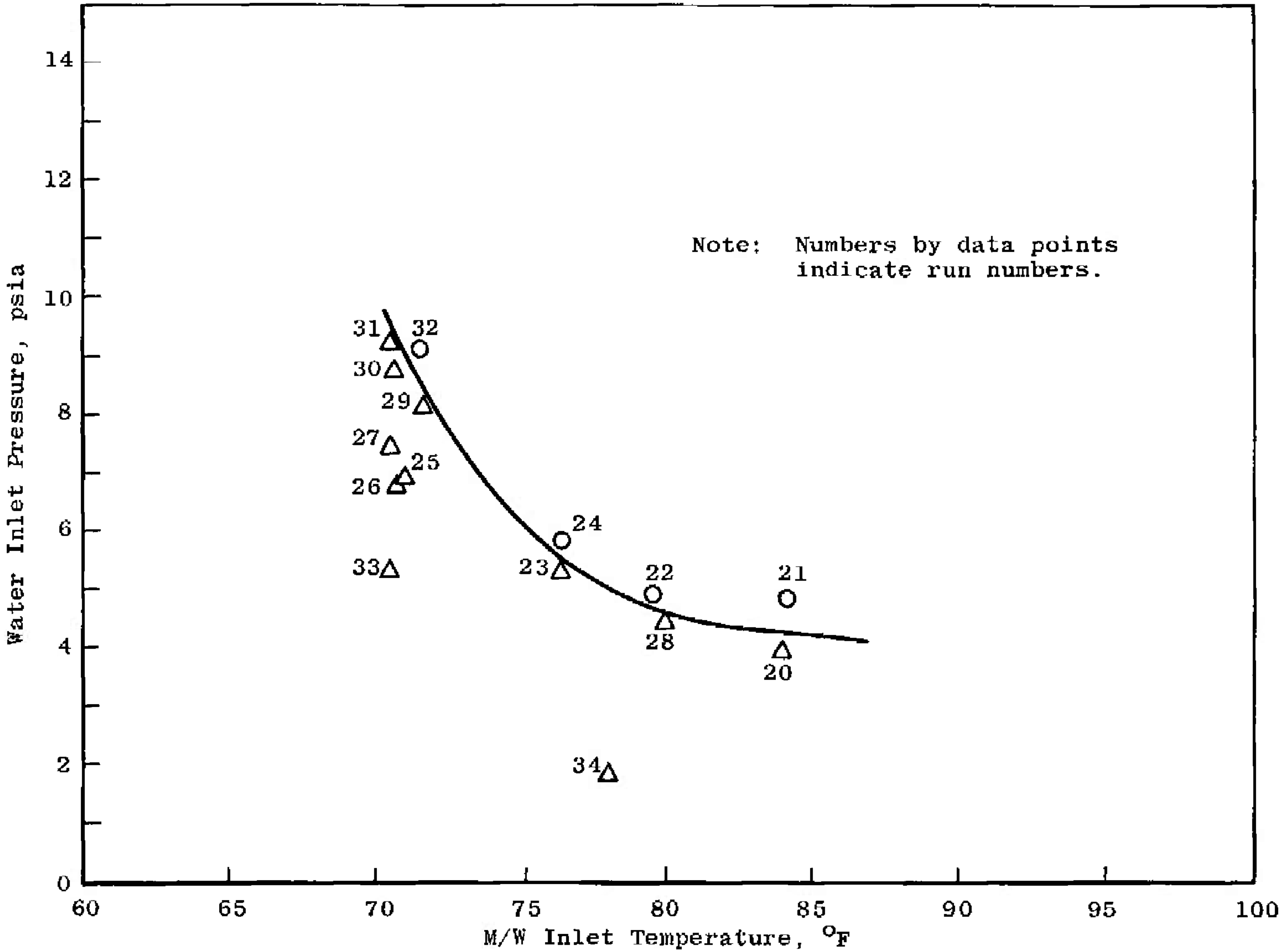


Fig. 41 Critical Starting Conditions Plot for SN5 without Flowmeter

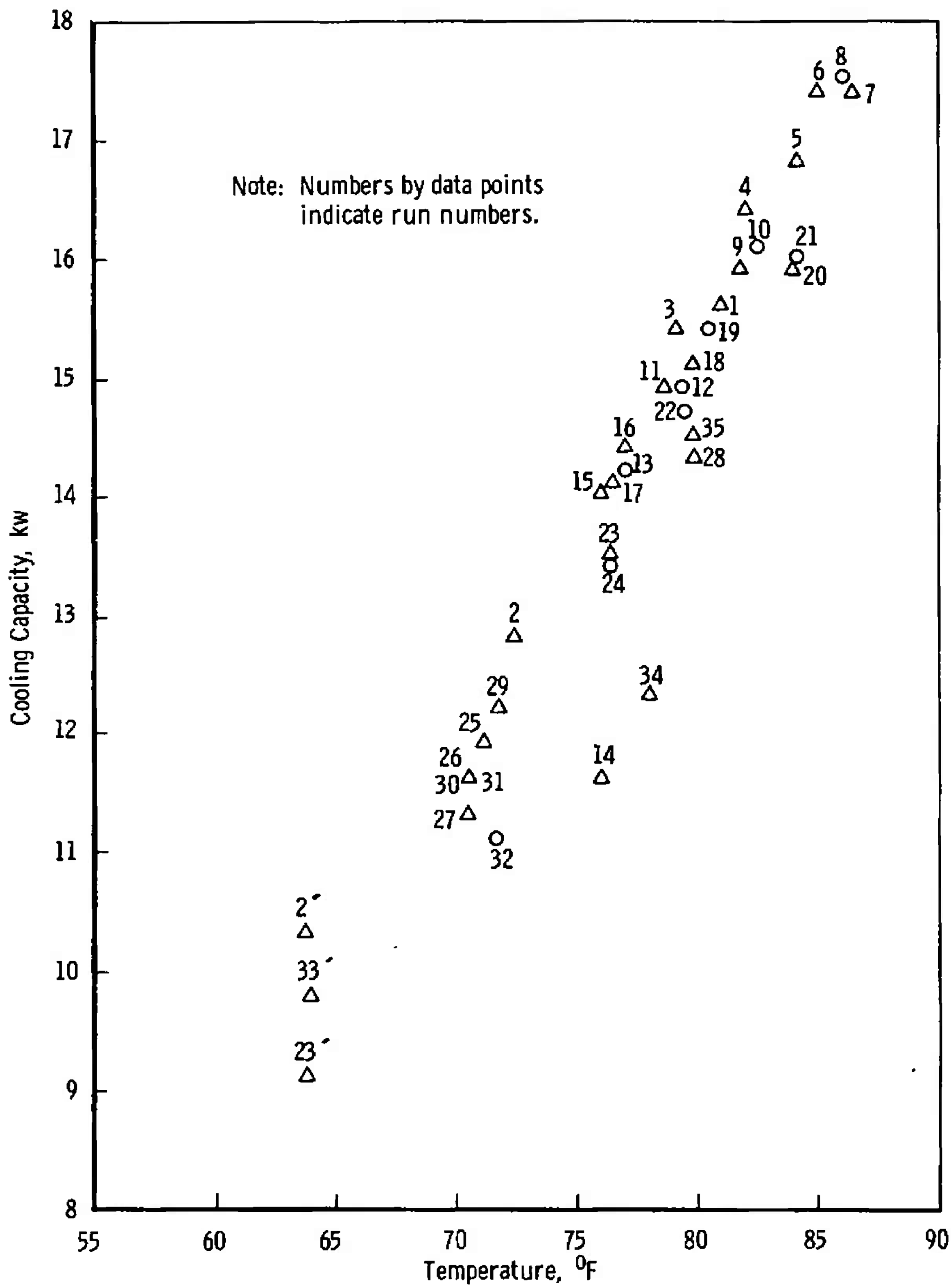


Fig. 42 Refrigeration Capacity Plot for SN5′

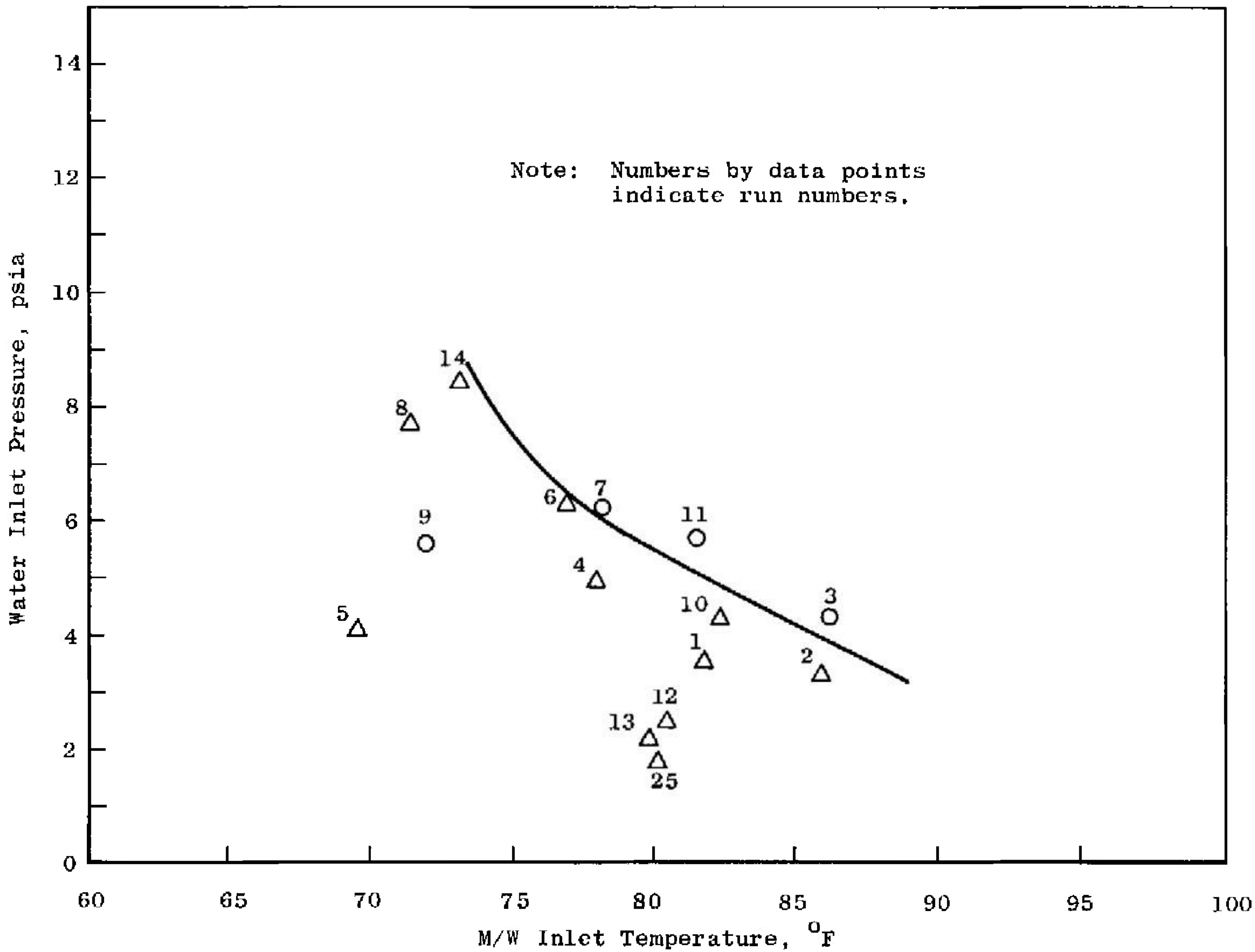


Fig. 43 Critical Starting Conditions Plot for SN7' with Flowmeter

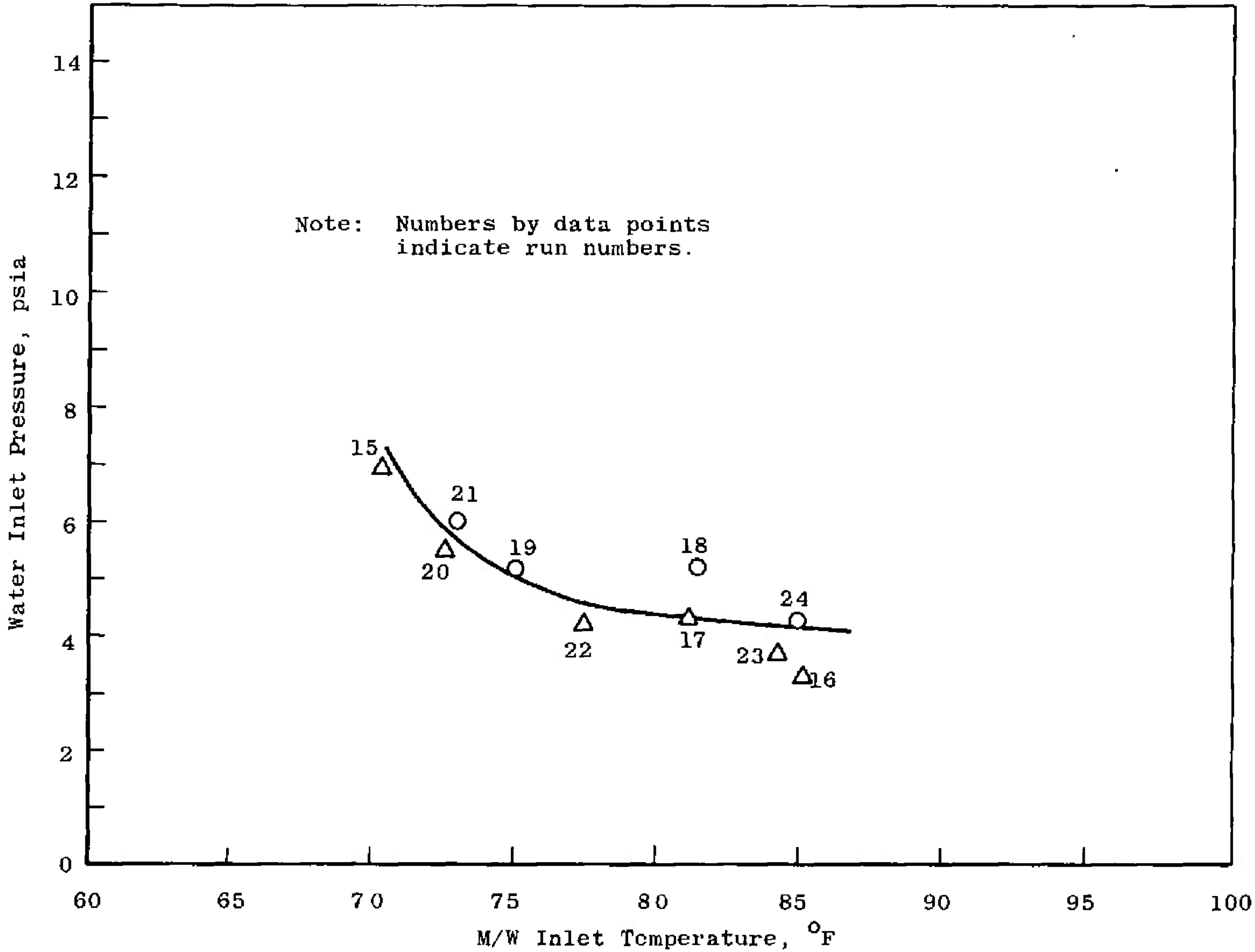


Fig. 44 Critical Starting Conditions Plot for SN7 ' without Flowmeter

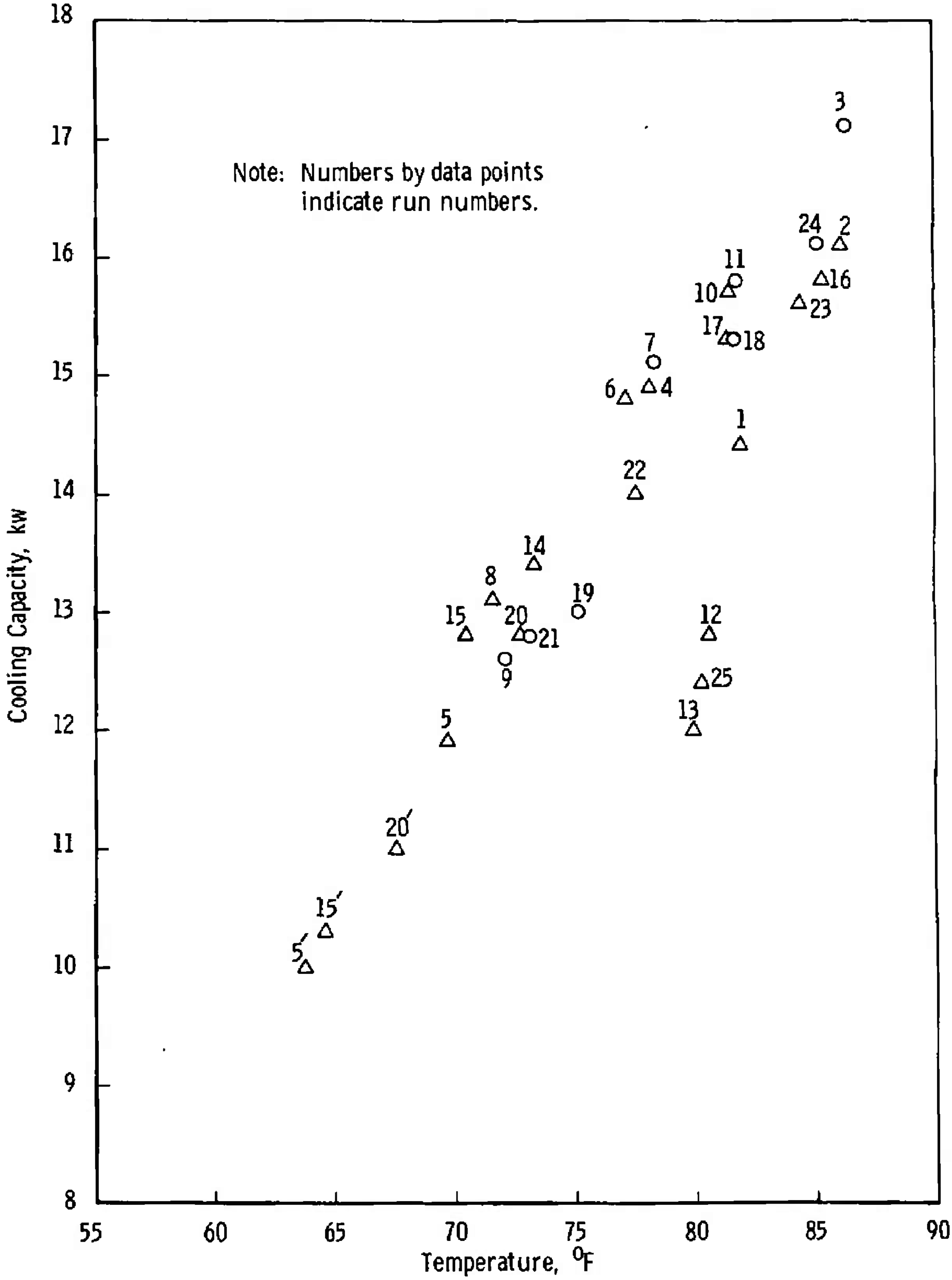


Fig. 45 Refrigeration Capacity Plot for SN7'

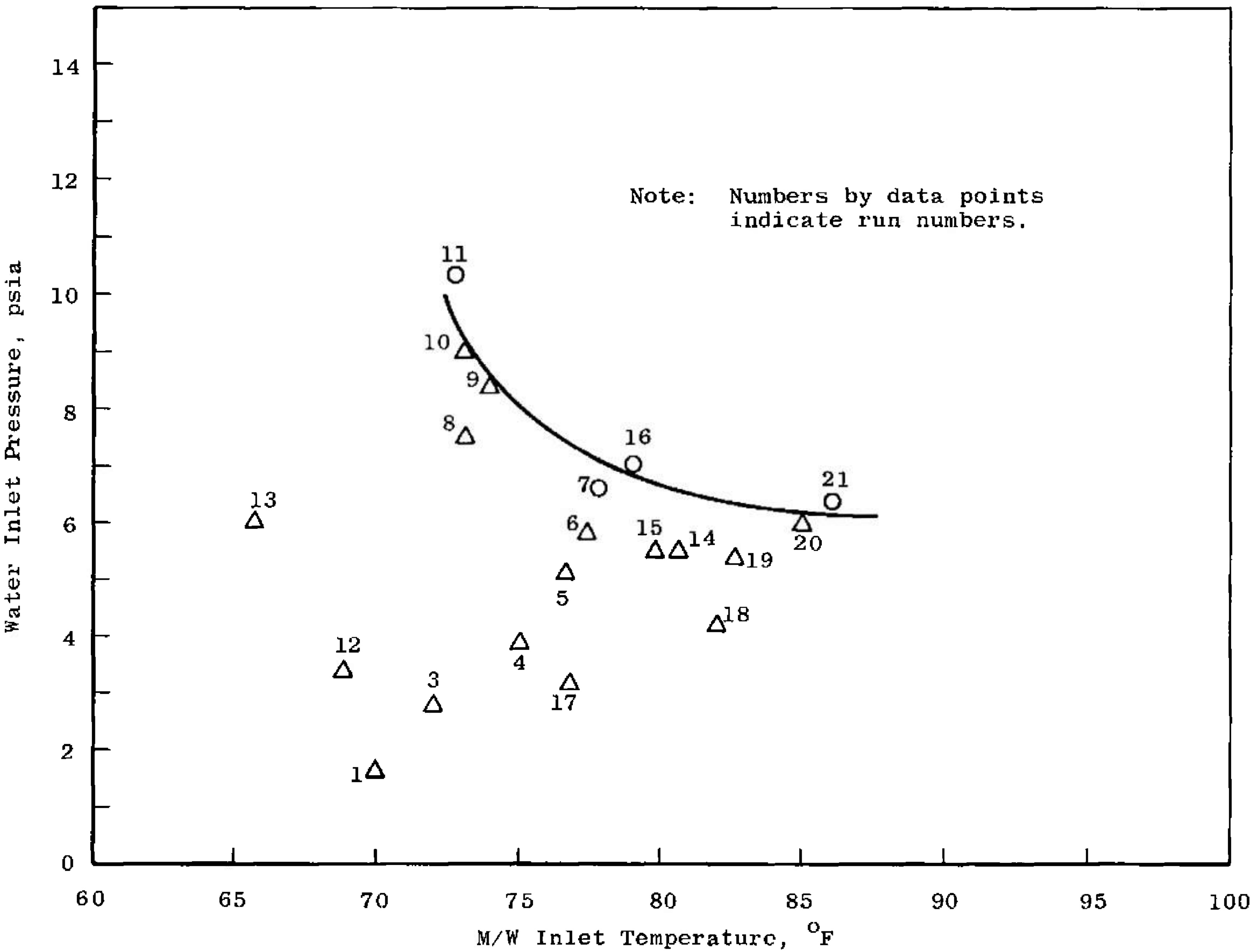


Fig. 46 Critical Starting Conditions Plot for SN9 ´with Flowmeter

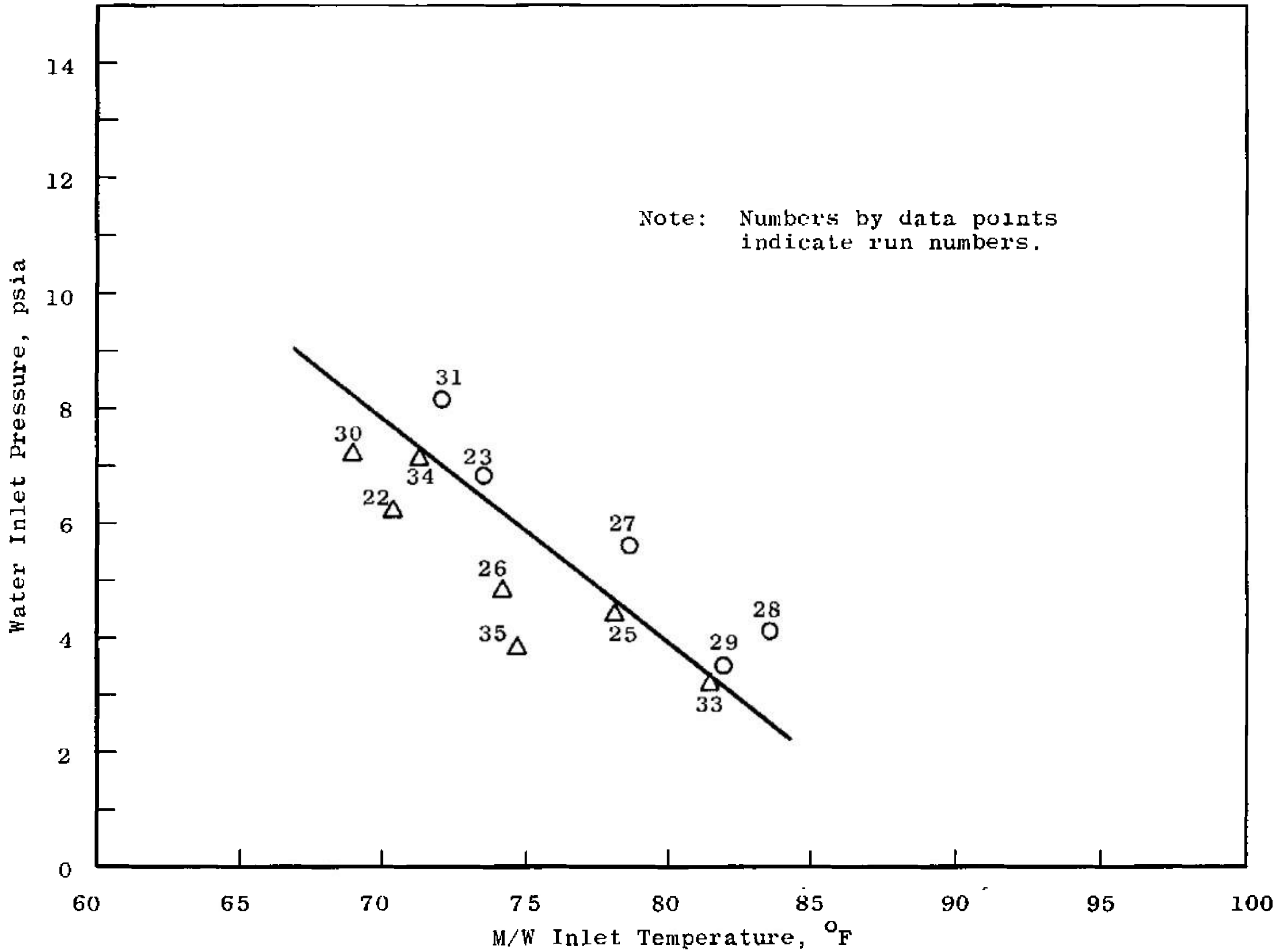


Fig. 47 Critical Starting Conditions Plot for SN9' without Flowmeter

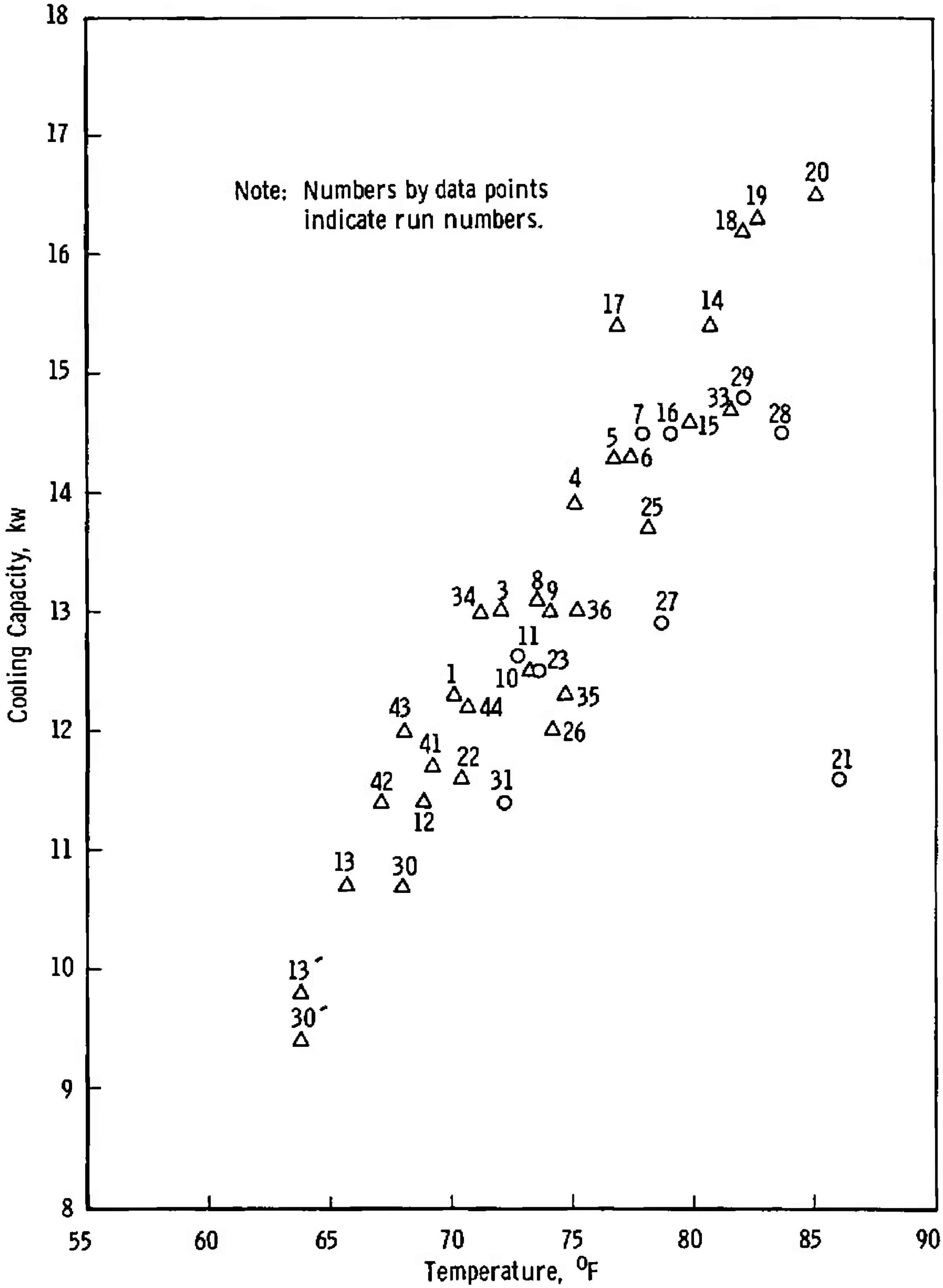


Fig. 48 Refrigeration Capacity Plot for SN9´

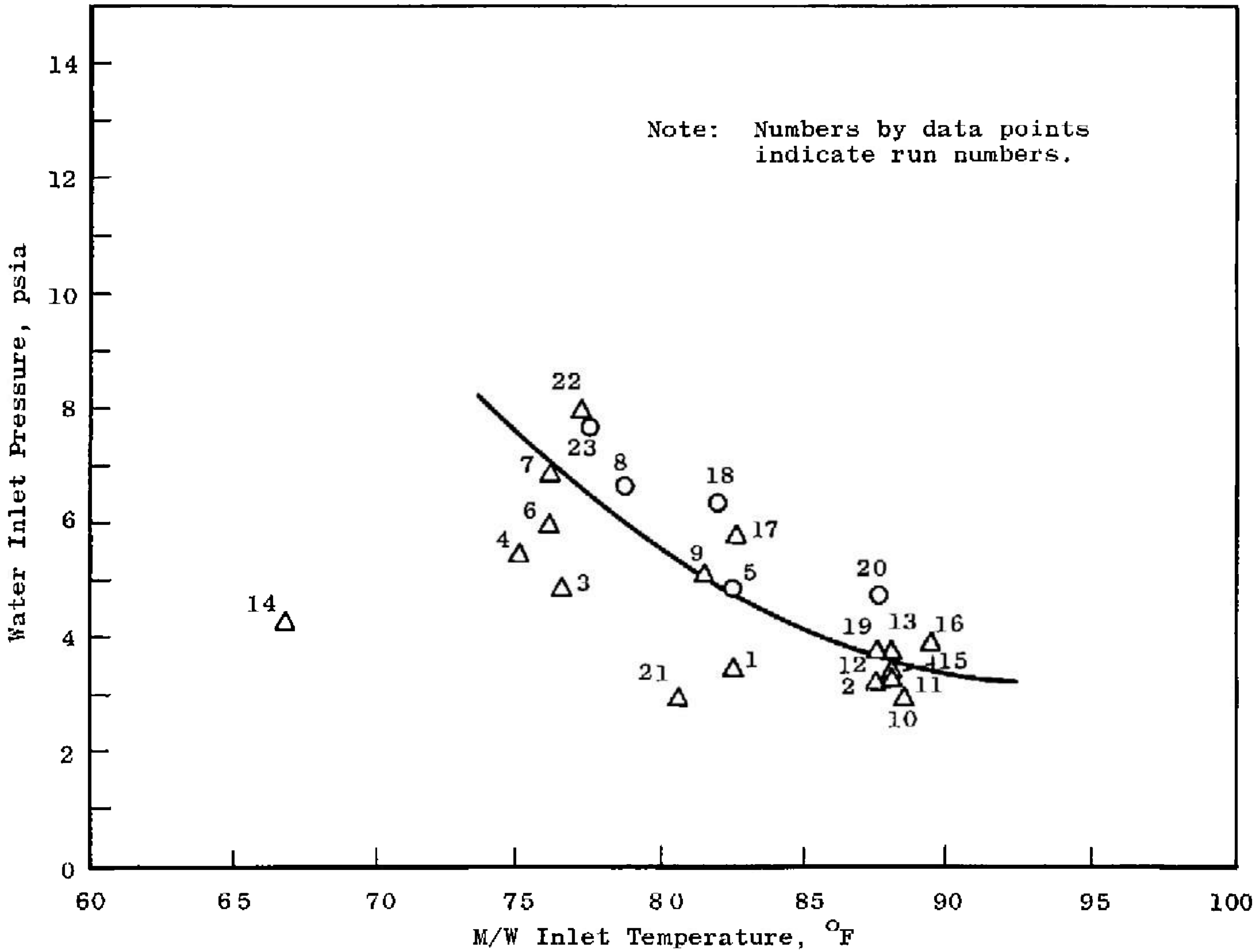


Fig. 49 Critical Starting Conditions Plot for SN6' with Flowmeter

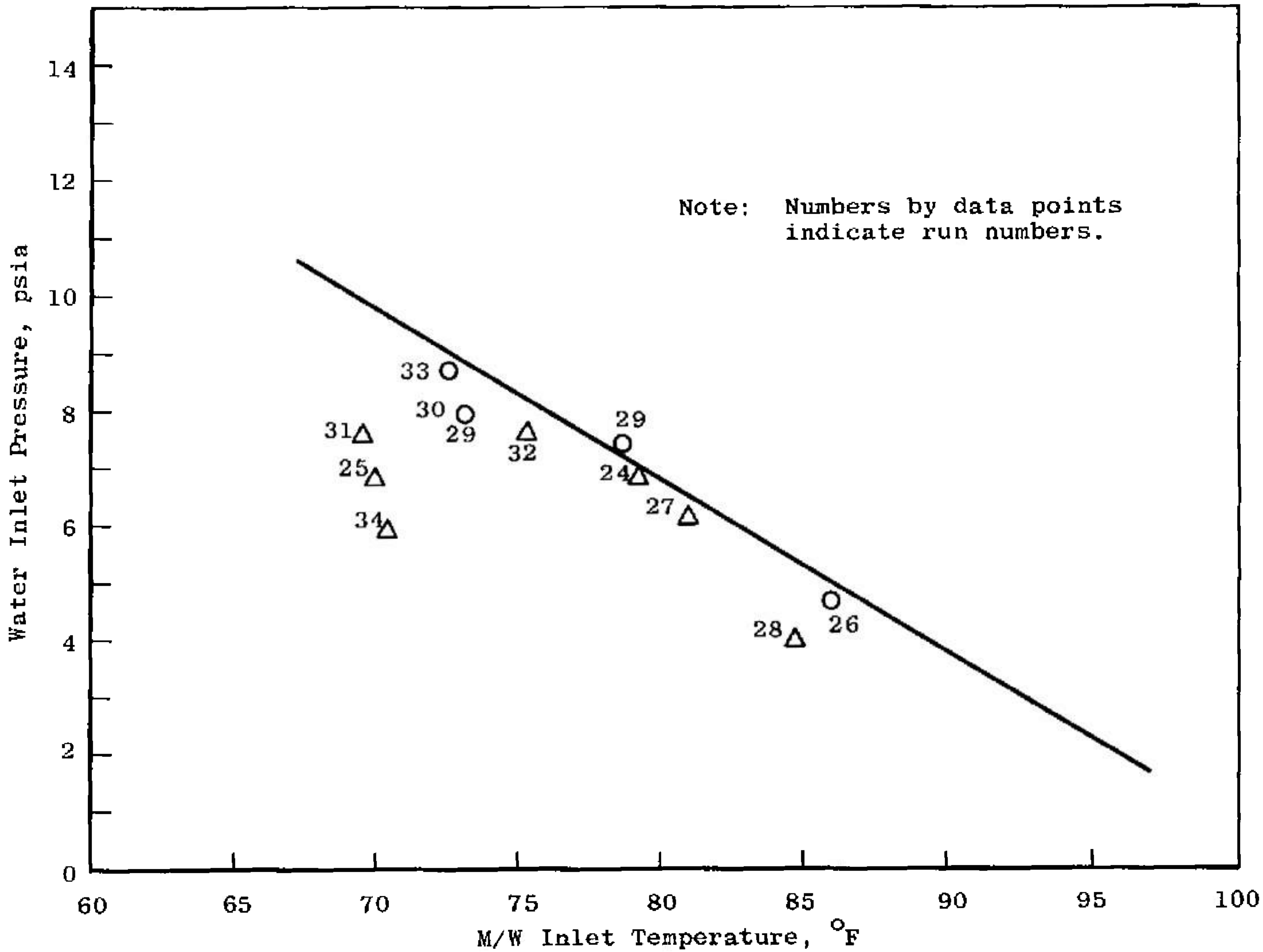


Fig. 50 Critical Starting Conditions Plot for SN6' without Flowmeter

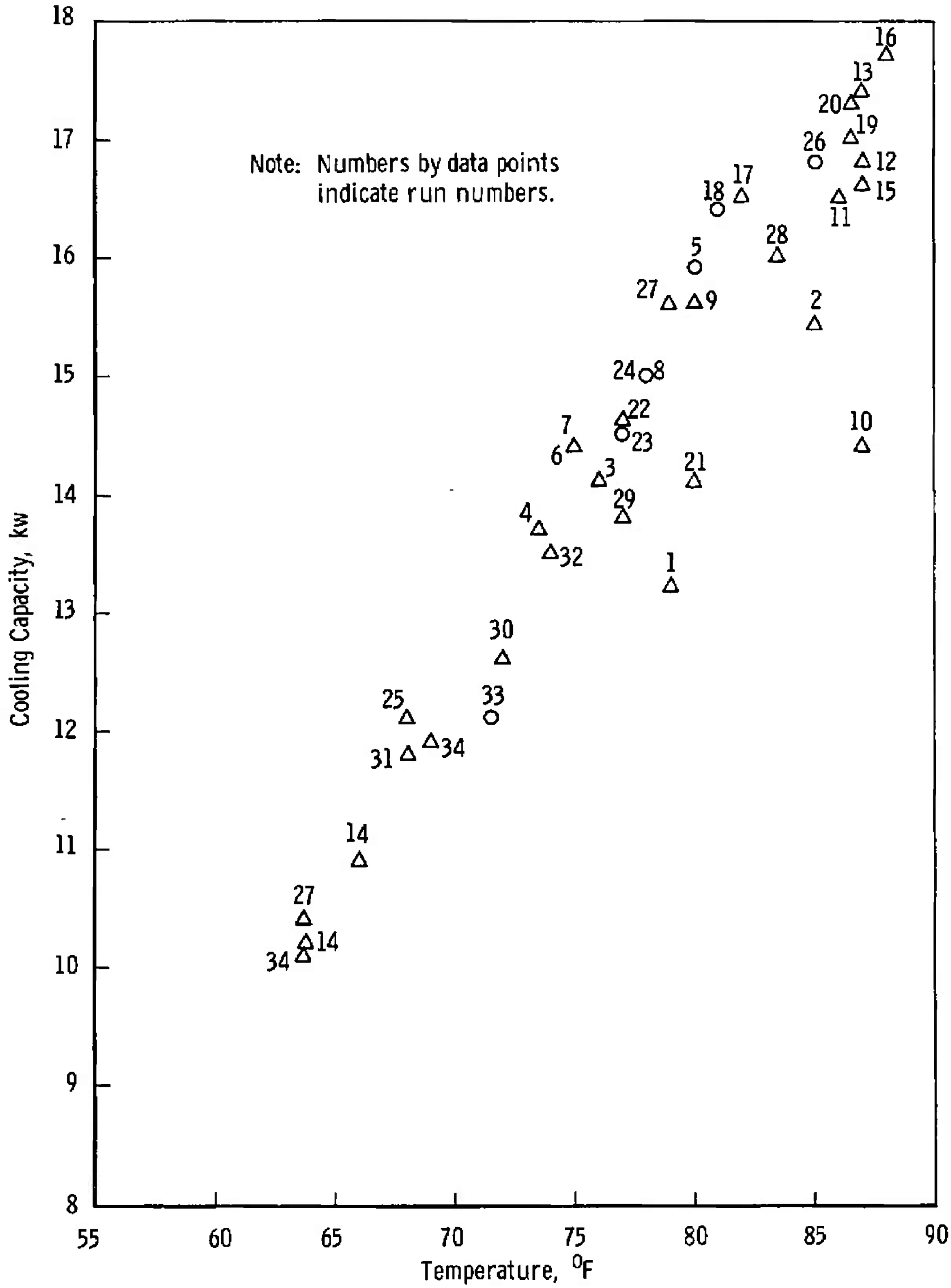


Fig. 51 Refrigeration Capacity Plot for SN6

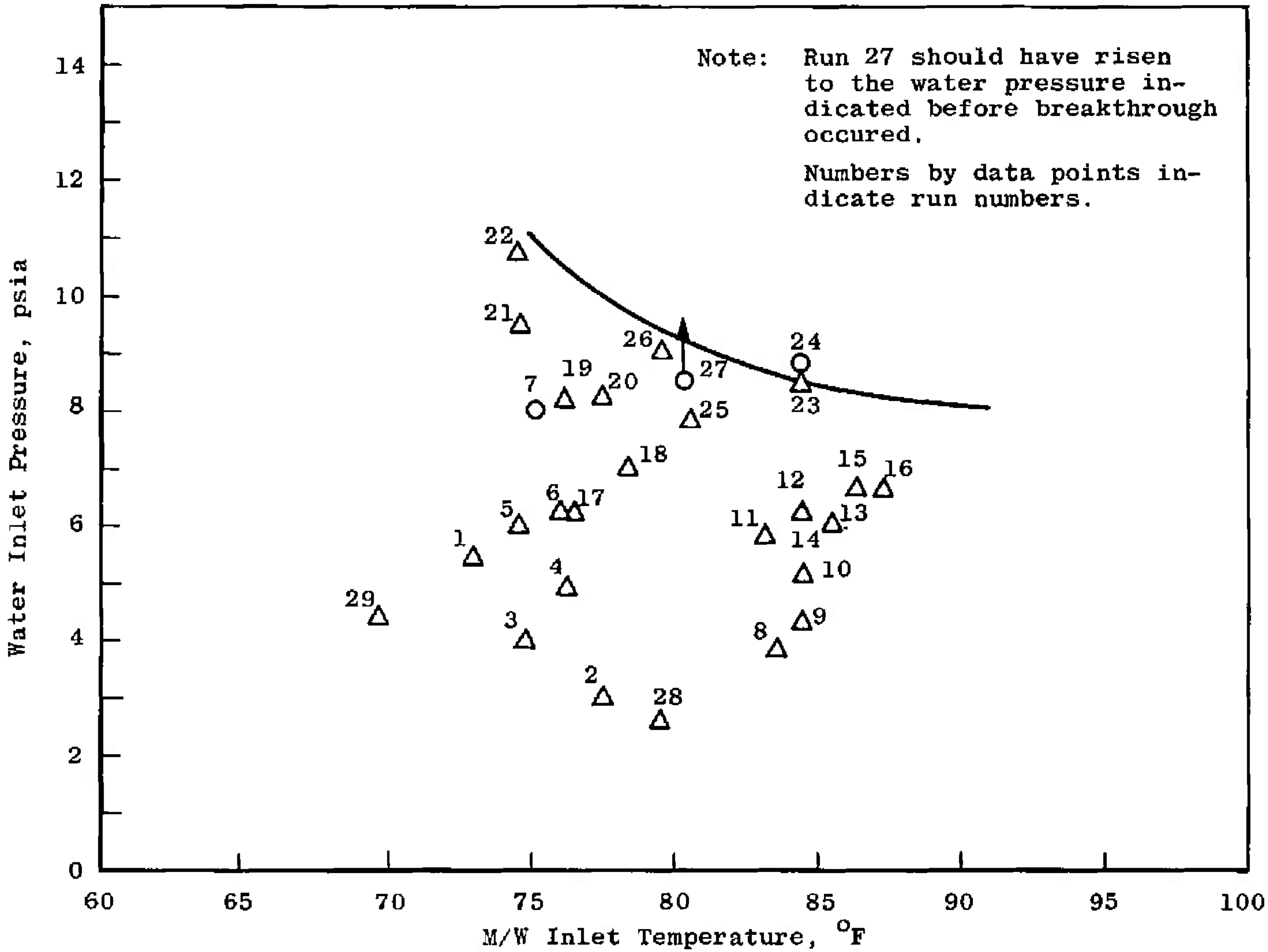


Fig. 52 Critical Starting Conditions Plot for SN11

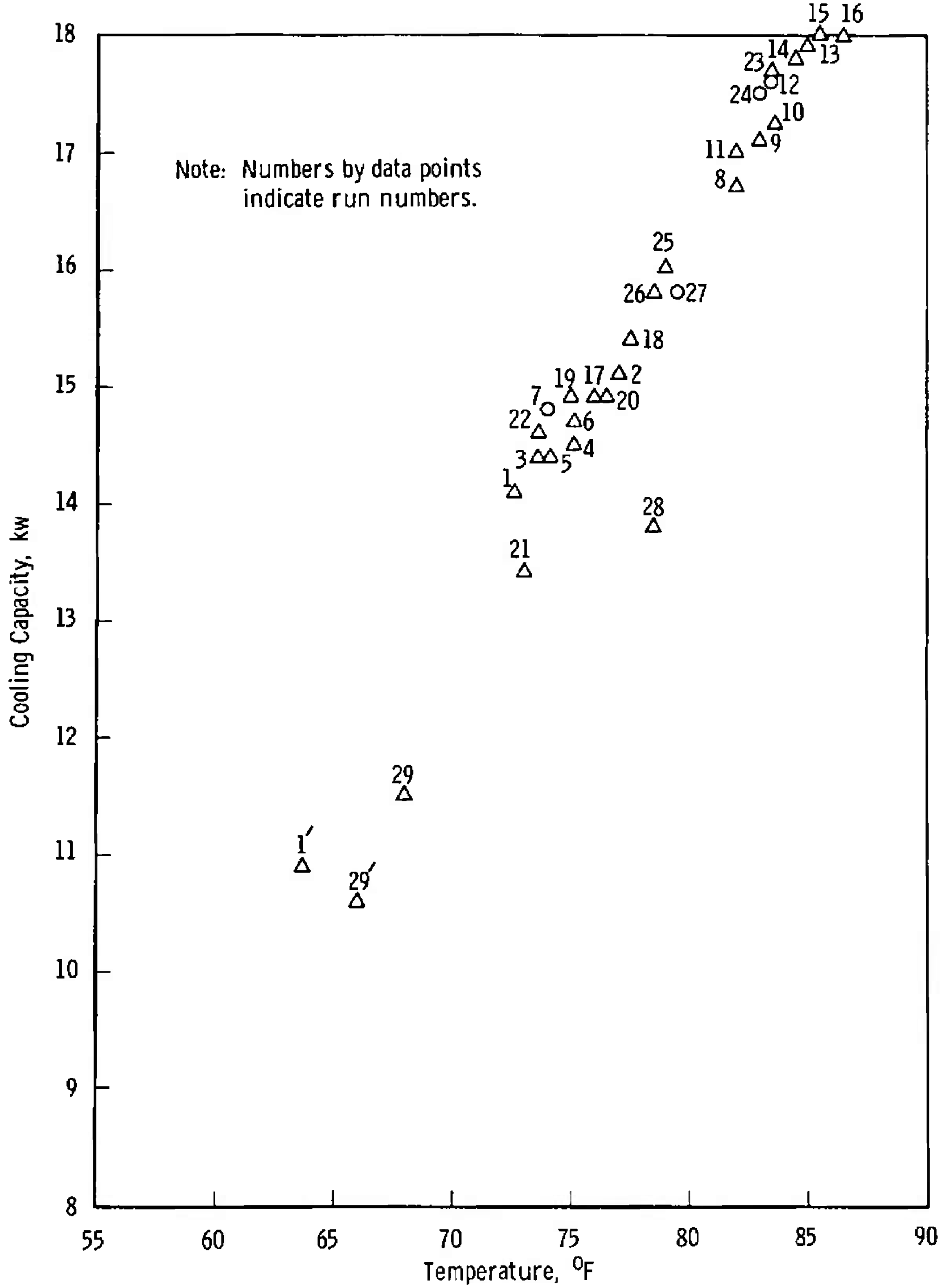


Fig. 53 Refrigeration Capacity Plot for SN11'

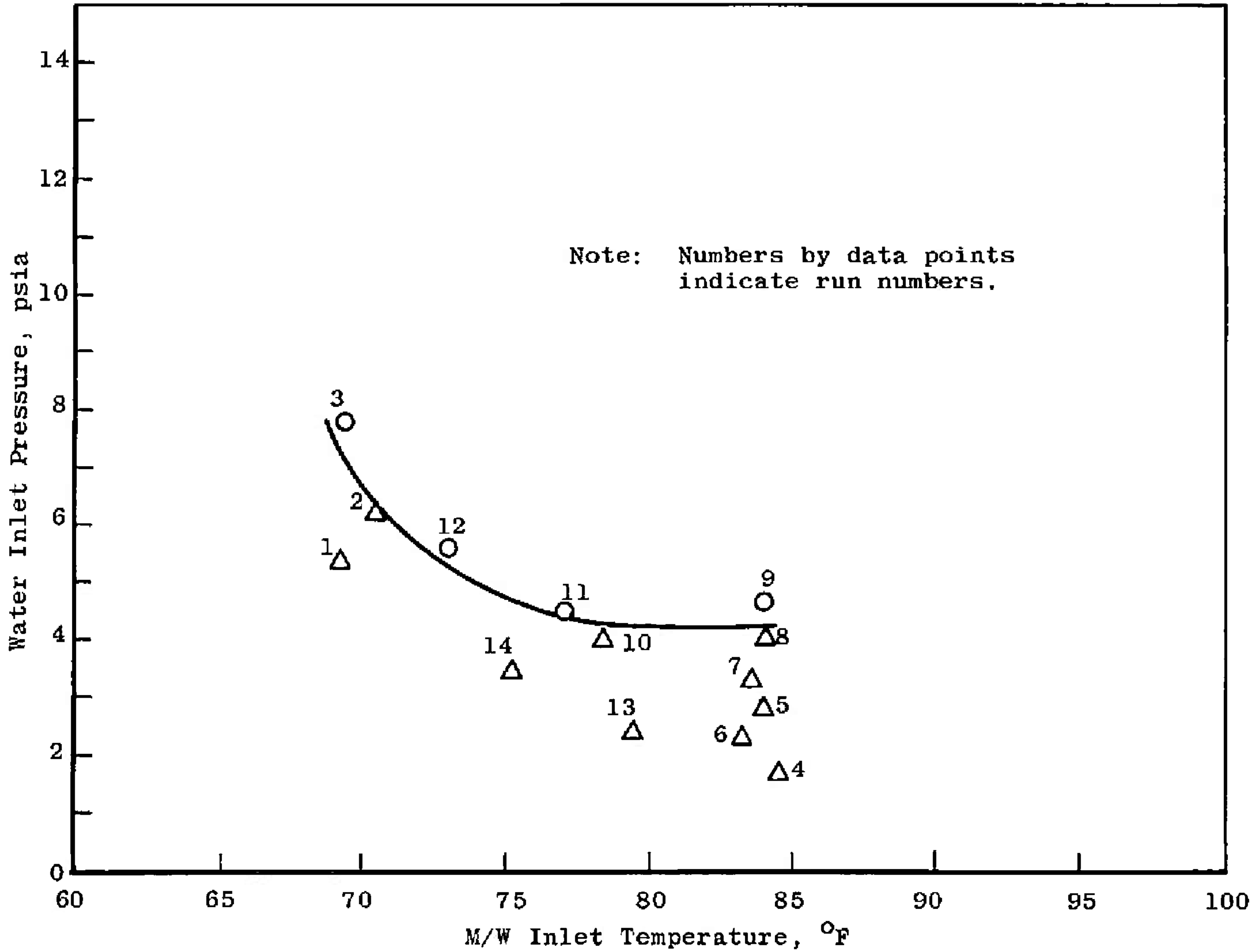


Fig. 54 Critical Starting Conditions Plot for SN13'

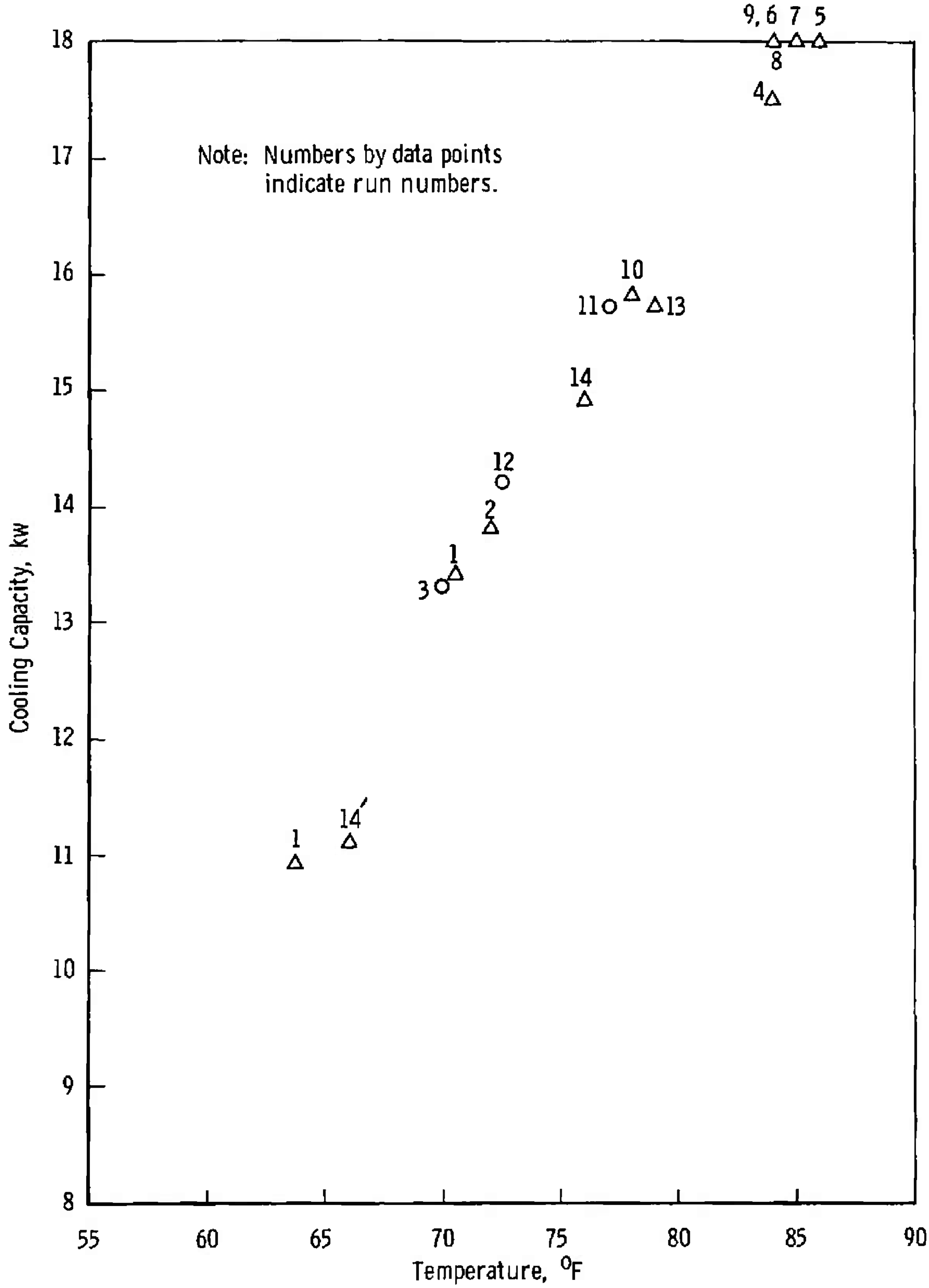


Fig. 55 Refrigeration Capacity Plot for SN13'

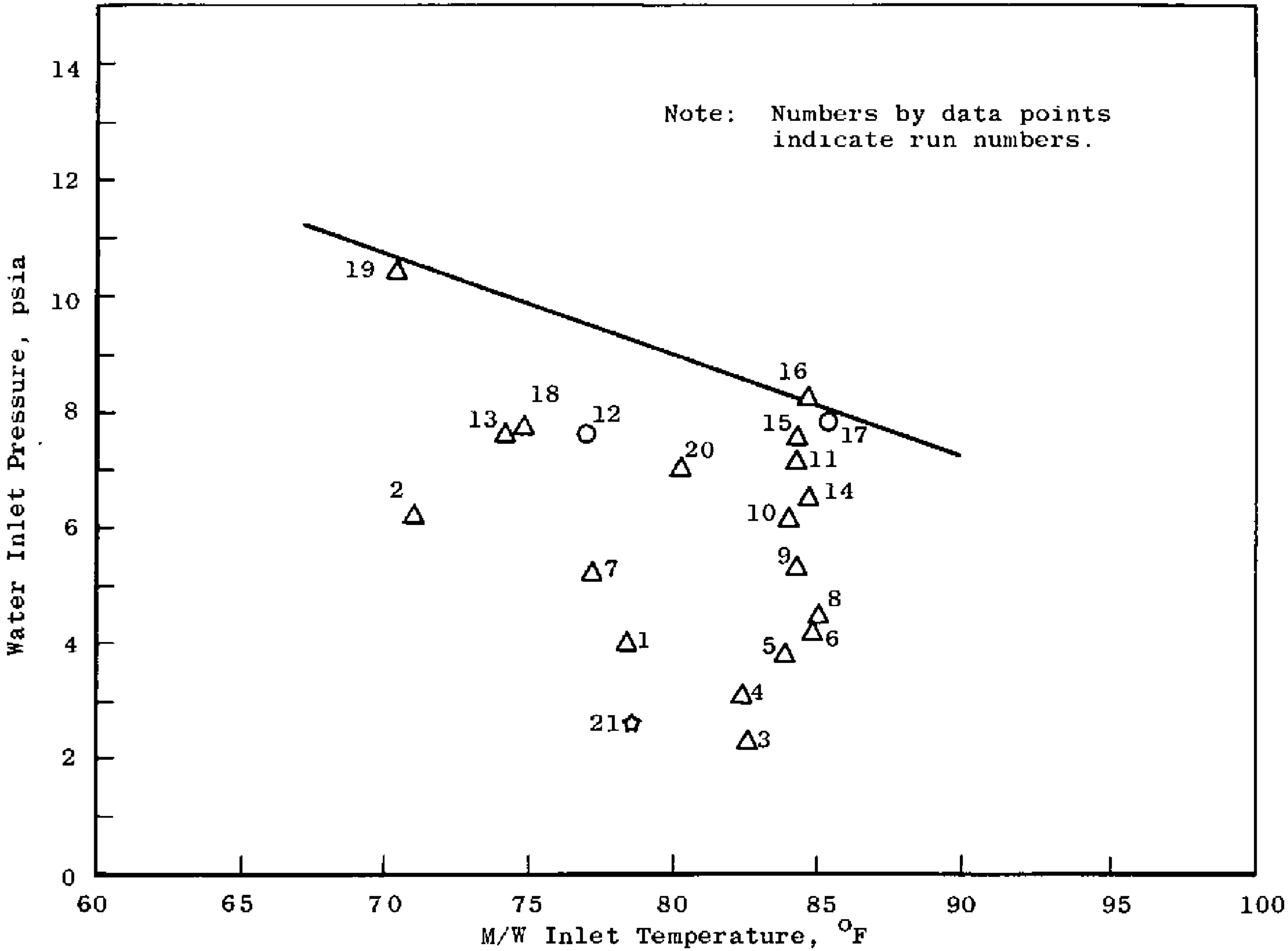


Fig. 56 Critical Starting Conditions Plot for SN10'

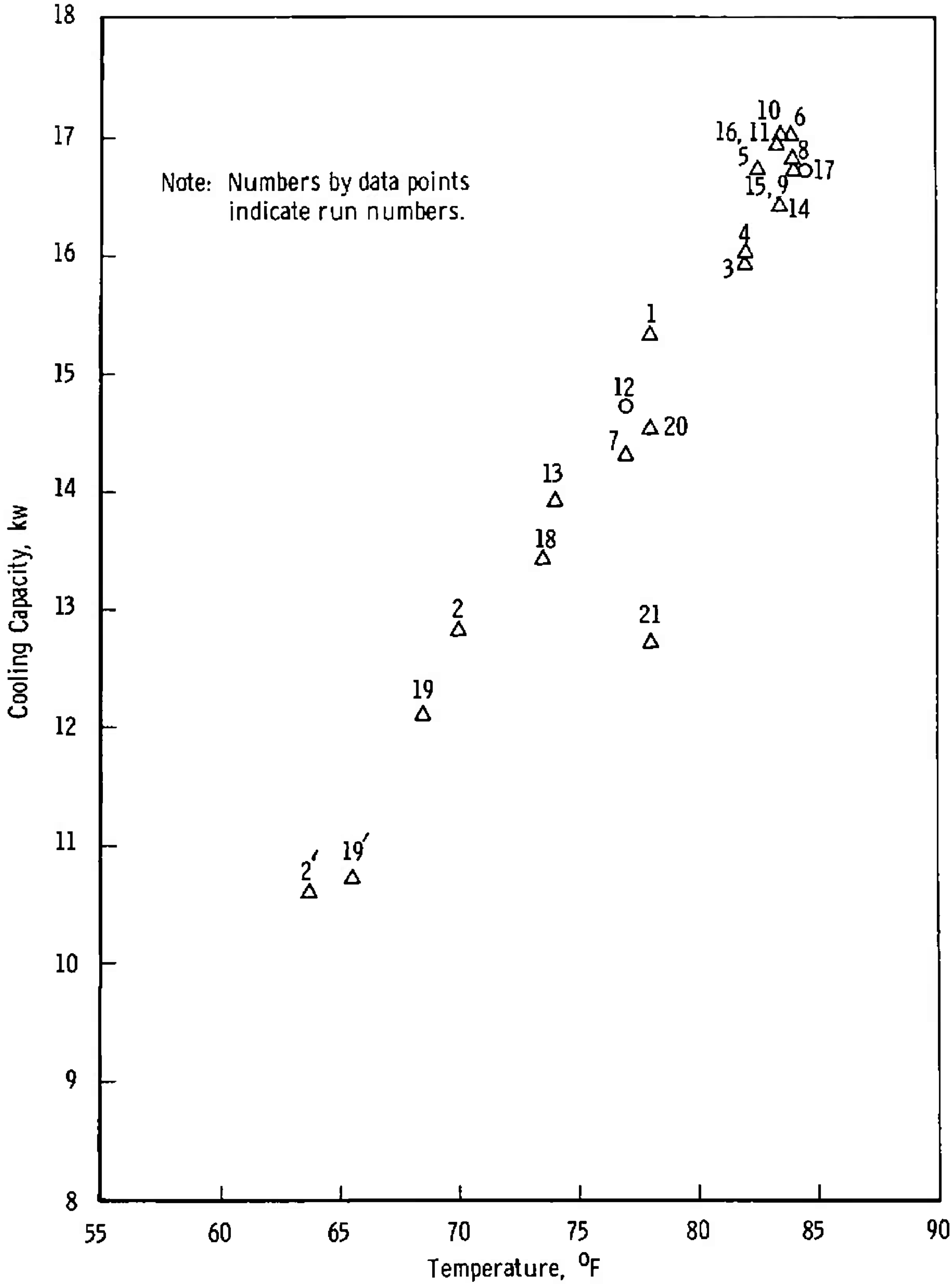


Fig. 57 Refrigeration Capacity Plot for SN10′

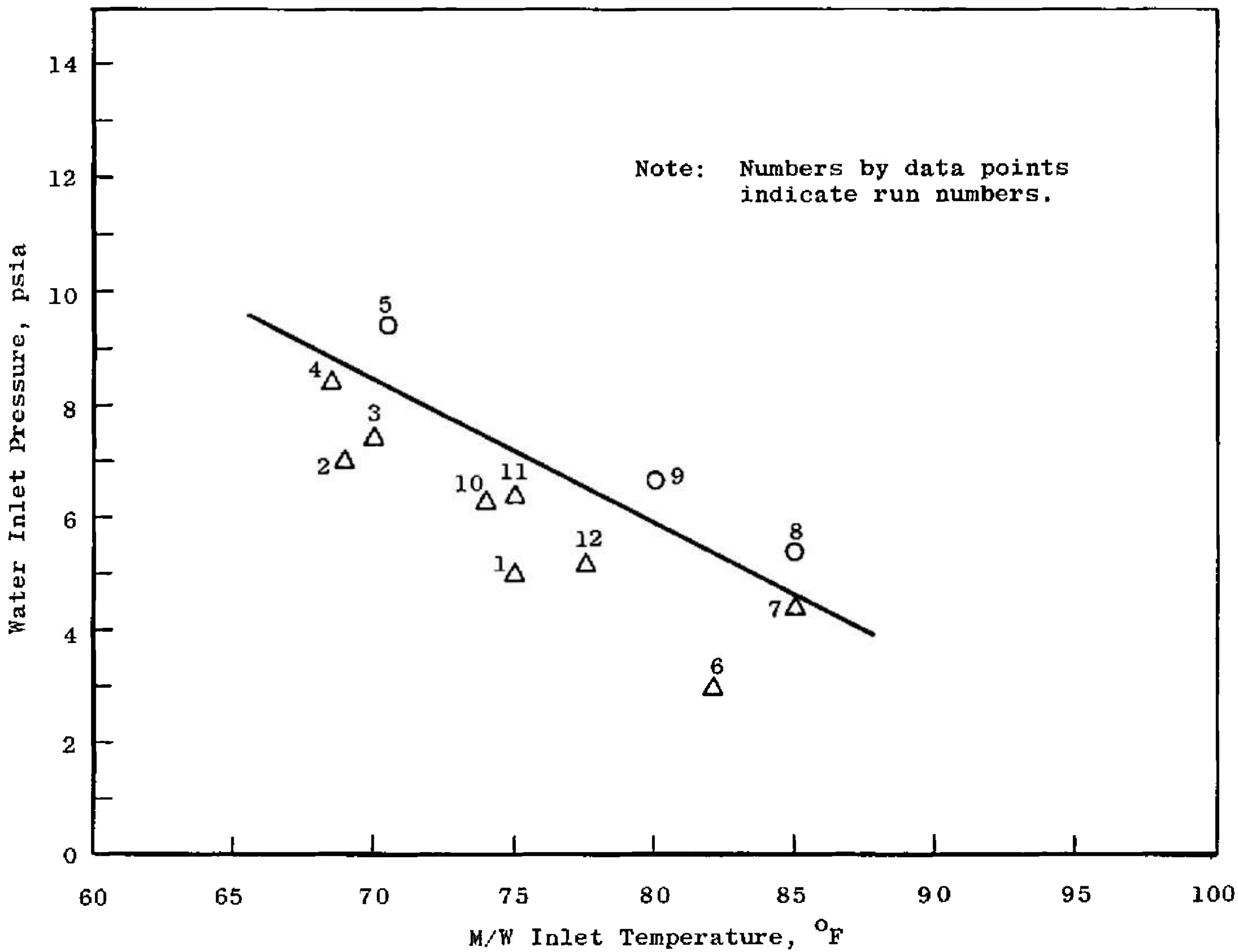


Fig. 58 Critical Starting Conditions Plot for SN12'

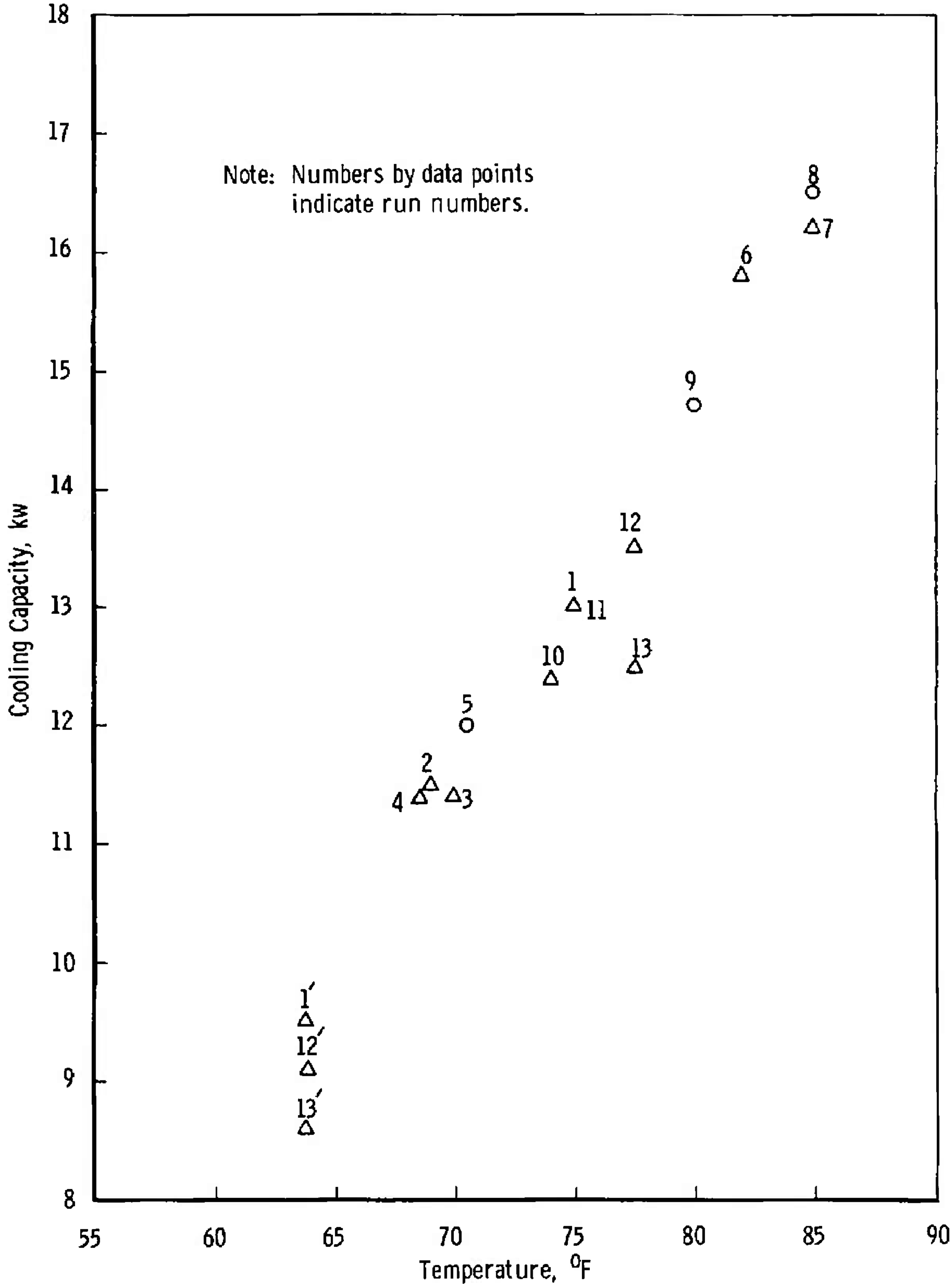


Fig. 59 Refrigeration Capacity Plot for SN12'

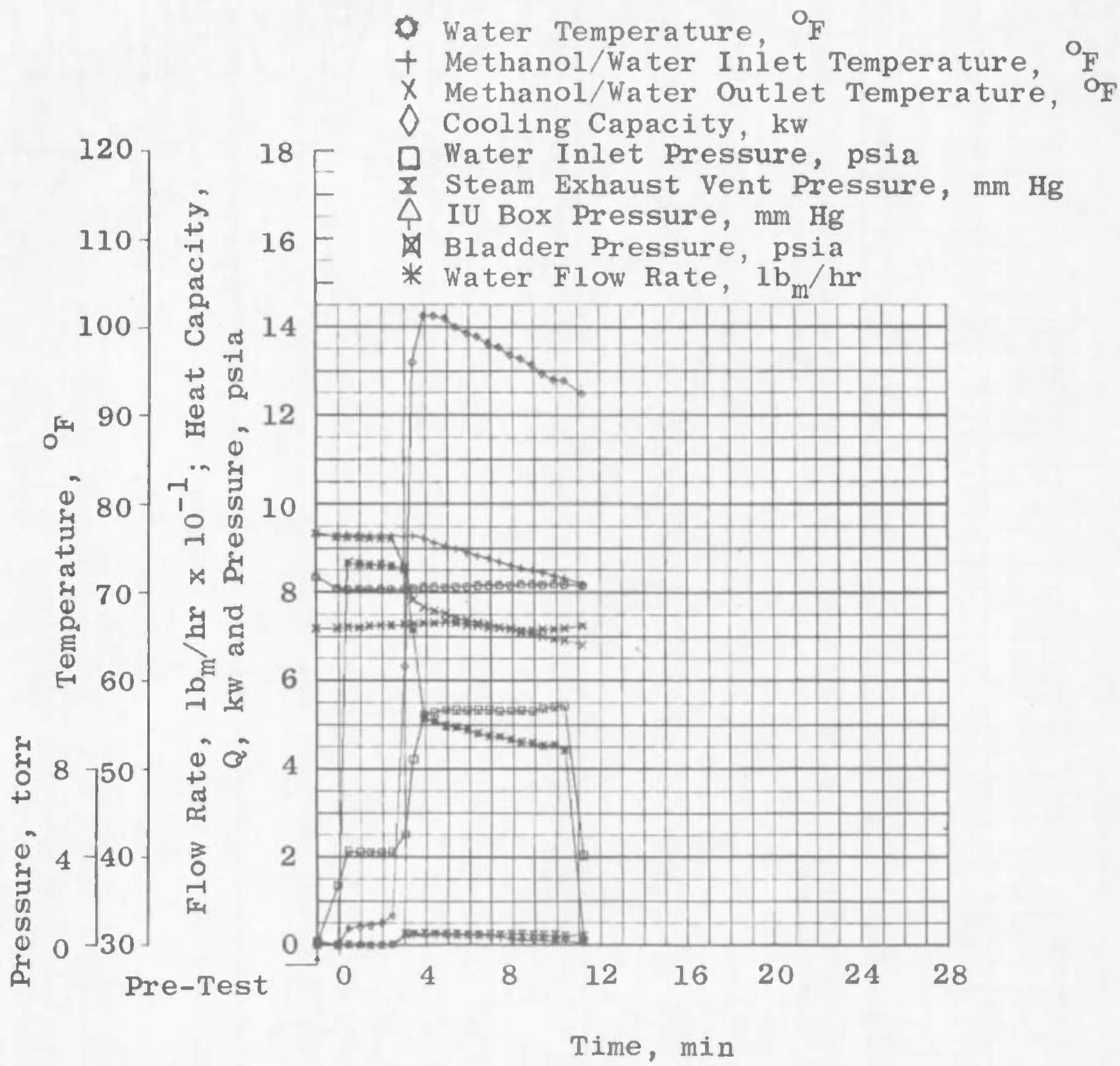


Fig. 60 Typical Complete Data Plot with Legend

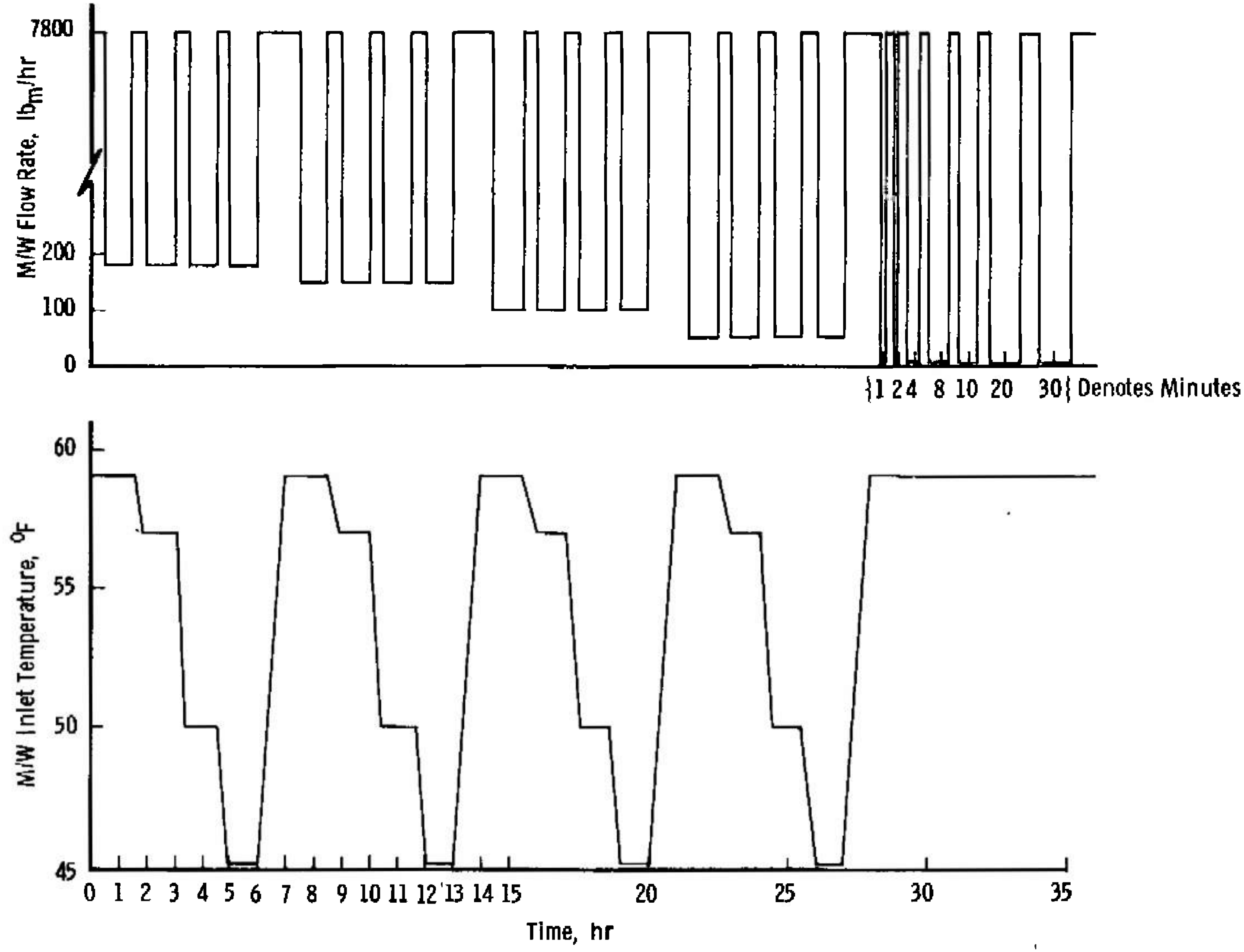


Fig. 61 Test Sequence for SN2

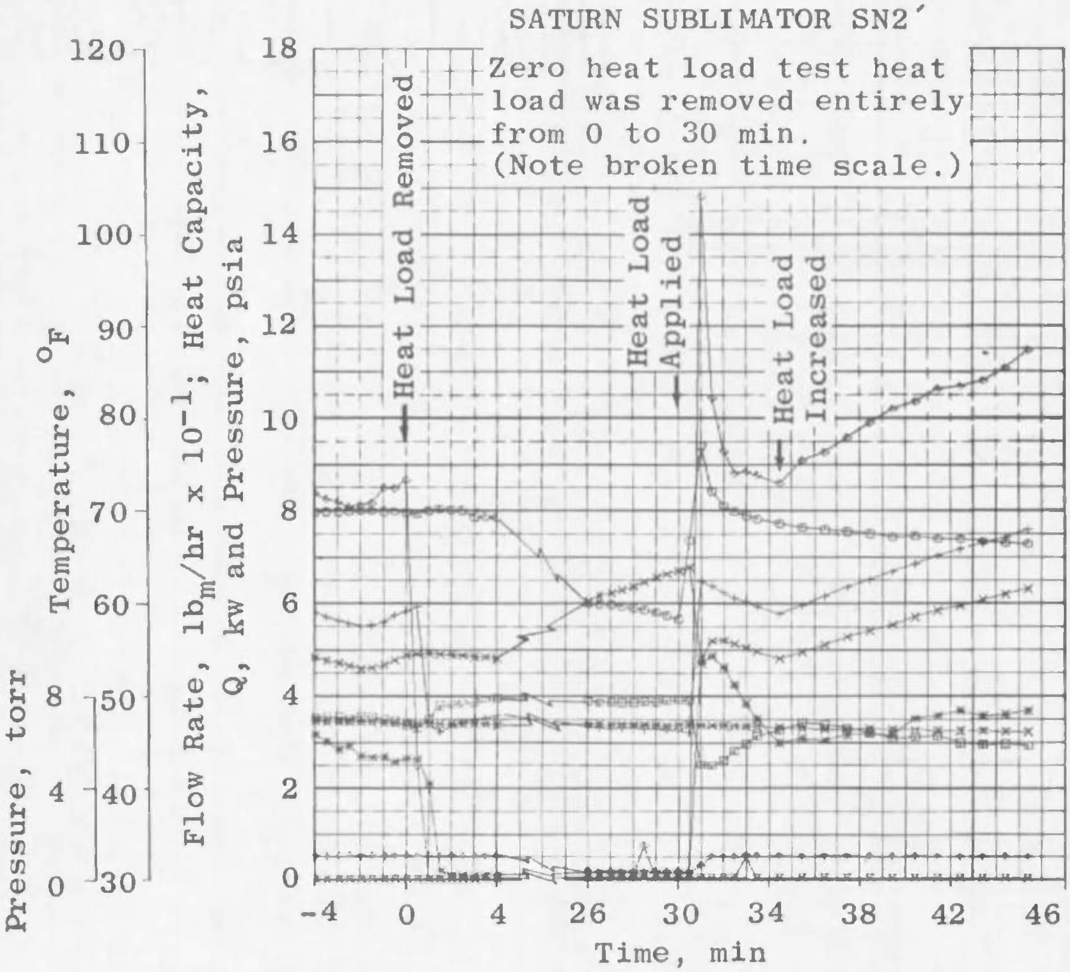


Fig. 62 Zero Heat Load Test Run on SN2′

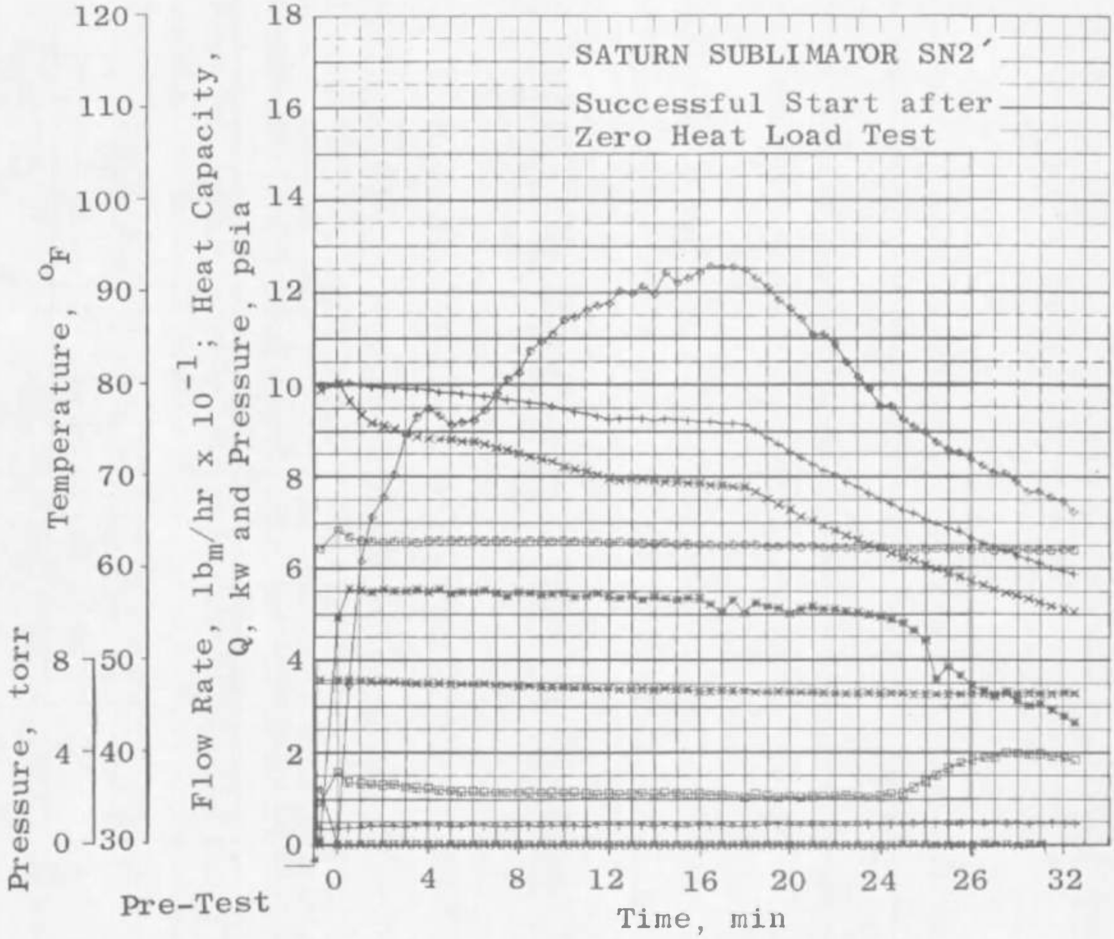


Fig. 63 Good Start after Zero Heat Load Test Run on SN2′

APPENDIX II
NASA SATURN SUBLIMATOR TEST DATA

SN10

Dates: From 12-7-65 through 1-7-66

Run No.	Fill Time, min		Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
								Flowmeter		Orifice Reg		
	Start	Comp	Start	Comp	Start	Comp		With	W/O	With	W/O	
1	6.0	7.0	0.2	1.0	62.0	61.8	8.9	x			x	
2	1.0	3.0	1.8	2.4	58.2	58.2	7.8		x		x	
3	3.5	4.5	3.4	4.1	80.5	80.5	14.0		x		x	
4	2.5	3.5	4.8	4.7	69.0	68.8	8.5		x		x	BT at 4.0 min
5	0.5	1.5	4.2	4.4	74.0	74.0	12.0		x		x	BT at 1.5 min
6	1.0	2.0	4.1	4.7	63.0	62.8	8.8		x		x	BT at 2.0 min
7	0.5	1.5	4.0	4.0	82.8	82.8	16.0		x		x	BT at 1.5 min
8	1.5	2.5	3.2	3.7	78.0	77.9	14.4		x		x	BT at 2.5 min
9	1.0	2.0	3.4	3.9	67.9	67.9	10.8		x		x	BT at 2.0 min
10	4.0	5.0	1.0	1.4	70.8	70.7	9.8		x		x	
11	8.5	9.0	2.9	4.0	65.0	65.0	10.0		x		x	
12	2.0	3.0	1.9	2.7	73.0	72.8	12.2		x		x	

SN10 (Continued)

Dates: From 12-7-65 through 1-7-66

Run No.	Fill Time, min		Water Inlet Pressure, P-1 psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
								Flowmeter		Orifice Reg		
	Start	Comp	Start	Comp	Start	Comp		With	W/O	With	W/O	
13	4.0	4.5	2.1	2.5	84.2	84.0	15.3		x		x	
14	2.5	4.0	1.7	2.3	82.4	82.1	14.5		x		x	
15	1.5	2.0	2.4	3.2	82.2	82.0	15.0		x		x	
16	4.0	4.5	4.0	5.5	63.5	63.5	9.6		x		x	
17	1.5	2.0	4.4	4.8	63.2	63.2	8.6		x		x	BT at 2.0 min
18	3.0	4.0	2.4	3.2	76.8	76.8	13.2		x		x	
19	9.2	9.5	3.3	4.4	74.5	74.4	12.8		x		x	Solenoid valve opened at 7.0 min
20	2.2	2.5	3.7	5.0	75.5	75.4	12.8		x		x	BT at 3.9 min
21	2.5	2.7	3.0	4.0	69.5	69.5	11.2		x		x	
22*	6.0	6.2	3.0	3.6	70.0	70.0	11.0		x		x	Solenoid valve opened at 3.0 min
23*	3.2	3.5	3.0	3.5	78.5	78.5	13.8		x		x	
24**	2.2	2.4	4.0	5.4	71.5	71.5	11.8		x		x	BT at 7.5 min

*Bubble Test
**Force BT increased T-2.

SN10 (Continued)

Dates: From 12-7-65 through 1-7-66

Run No.	Fill Time, min		Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
								Flowmeter		Orifice Reg		
	Start	Comp	Start	Comp	Start	Comp		With	W/O	With	W/O	
25	9.0	9.5	2.8	3.0	68.0	67.5	10.4		x	x		H_2O on at 6.0 min
26	5.5	9.5	2.3	3.2	72.0	69.0	11.4		x	x		H_2O on at 2.5 min
27	---	6.0	---	1.5	---	71.0	11.0		x	x		Good start but unable to distinguish fill
28	4.1	4.2	6.2	6.5	71.2	71.2	11.7		x	x		H_2O on at 2.5 min BT at 4.5 min
29	8.0	9.0	3.1	3.6	70.2	70.0	11.2		x	x		H_2O on at 6.5 min
30	3.0	8.0	1.5	3.7	71.5	68.5	10.8	x			x	
31	3.5	5.0	1.8	5.2	70.8	70.4	11.2	x			x	
32	7.5	9.5	2.0	5.8	70.8	69.9	11.0	x			x	H_2O on at 4.0 min
33	4.5	6.0	2.3	6.8	71.3	70.4	11.4	x			x	H_2O on at 2.0 min
34	1.5	3.0	2.1	5.7	83.2	82.0	14.7	x			x	
35	5.5	7.0	2.4	6.8	78.8	77.7	13.4	x			x	H_2O on at 2.0 min
36	6.0	7.0	2.5	6.5	82.8	82.4	14.7	x			x	H_2O on at 2.0 min BT at 7.0 min

SN10 (Continued)

Dates: From 12-7-65 through 1-7-66

Run No.	Fill Time, min		Water Inlet Pressure, P-1 psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
								Flowmeter		Orifice Reg		
	Start	Comp	Start	Comp	Start	Comp		With	W/O	With	W/O	
37	2.5	3.5	2.5	7.4	63.8	63.5	9.0	x			x	
38	5.5	6.0	2.4	7.4	72.5	72.2	11.6	x			x	
39	4.0	4.5	2.5	8.0	74.0	73.8	12.2	x			x	H_2O on at 1.0 min
40	5.0	5.5	3.0	8.0	80.0	79.7	13.9	x			x	H_2O on at 1.0 min
41	4.0	6.5	2.1	4.7	87.5	85.8	15.5	x			x	
42	8.0	10.5	1.0	2.0	69.2	68.0	9.8	x			x	
43	5.0	6.5	2.2	6.0	84.5	83.8	14.9	x			x	H_2O on at 1.0 min BT at 13.0 min
44	---	8.5	---	1.6	---	70.0	9.4	x			x	Good start but unable to distinguish fill
45	6.0	8.0	1.6	2.8	65.4	65.0	8.9	x			x	
46	12.5	14.5	1.7	2.3	77.6	76.9	12.0	x			x	H_2O on at 2.5 min BT at 18.5 min
47	3.5	5.0	1.8	4.6	69.7	69.0	10.5	x			x	
48	---	15.5	---	1.0	---	80.0	12.0	x			x	Good start but unable to distinguish fill

SN10 (Concluded)

Dates: From 12-7-65 through 1-7-66

Run No.	Fill Time, min		Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
								Flowmeter		Orifice Reg		
	Start	Comp	Start	Comp	Start	Comp		With	W/O	With	W/O	
49	14.0	21.0	0.8	1.7	72.4	69.0	10.0	x			x	
50	10.0	12.5	1.2	2.0	68.0	67.2	9.1	x			x	
51	5.0	6.0	2.6	2.9	83.8	83.0	14.3	x			x	BT at 6.0 min
52	2.5	3.2	2.8	6.1	80.8	80.2	13.8	x			x	BT at 3.5 min
53	---	11.0	---	1.3	---	69.0	9.0	x			x	Good start but unable to distinguish fill
54*	---	18.5	---	1.8	---	64.0	8.2	x			x	Good start but unable to distinguish fill
55*	---	18.0	---	1.5	---	63.0	6.7	x			x	Good start but unable to distinguish fill
56*	2.5	3.0	3.3	9.2	69.0	68.9	10.5	x			x	

*Hot H_2O supply

SN9

Dates: From 1-11-66 through 1-14-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	12.0	13.5	3.5	1.2	1.8	70.0	69.5	9.2	x		x		Solenoid valve opened at 2.5 min
2	3.5	4.0	8.0	2.1	5.9	75.0	72.5	11.9	x		x		
3	6.6	8.5	5.5	1.6	3.3	83.0	82.0	14.1	x		x		
4	5.0	5.5	8.2	2.2	6.0	84.0	83.5	15.2	x		x		
5	3.9	4.5	9.5	2.8	7.8	68.9	68.6	10.3	x			x	
6	5.8	7.2	6.1	1.9	3.6	87.5	87.0	16.0	x			x	BT at 8.8 min 86°F
7	8.0	9.0	5.9	1.8	3.7	86.0	83.7	15.2	x			x	
8	5.0	5.3	8.0	2.4	6.1	78.7	78.2	13.2	x			x	
9	18.0	20.0	3.5	1.2	1.6	72.5	70.5	10.4	x			x	
10	3.2	3.4	4.5	3.2	3.7	65.4	65.4	9.0		x		x	
11	3.0	3.2	4.0	3.0	3.5	64.8	64.8	8.7		x		x	
12	3.2	3.5	4.2	3.3	3.6	75.0	75.0	11.8		x		x	
13	3.7	4.1	3.9	2.9	3.4	85.0	85.0	14.9		x		x	
14	2.8	3.0	5.1	3.4	3.7	76.2	76.2	12.1		x		x	
15	2.0	2.3	5.8	4.2	4.8	76.1	76.0	11.9		x		x	
16	1.9	2.0	7.3	5.1	6.3	66.4	66.4	9.4		x		x	
17	2.0	2.3	6.3	4.5	5.6	75.9	75.3	12.0		x		x	
18	1.8	1.9	8.1	5.8	7.4	74.6	74.6	12.0		x		x	
19	4.2	4.5	3 6	2.4	2.7	83.2	83.2	14.0		x		x	
20	2.3	2.4	6.0	4.4	5.6	80.4	79.2	13.5		x		x	

SN4, 0.068 in.

Dates: From 1-24-66 through 2-7-66

Run No.	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	GS	11.0	12.5	4.0	1.4	2.0	70.8	78.9	9.5	x		x		H_2O on at 2.5 min
2	GS	6.5	7.5	3.4	3.5	4.9	65.0	64.7	10.1	x		x		H_2O on at 2.5 min
3	No Run	-	---	5.4	0.5	0.5	81.5	81.5	0	x		x		Would not fill, no cooling
4	GS	17.0	24.0	4.5	0.8	2.7	68.0	67.0	10.3	x		x		
5	GS	5.0	5.9	6.5	2.4	3.5	70.4	69.6	11.6	x		x		
6	GS	4.5	5.5	6.7	2.8	4.6	70.4	69.7	12.1	x		x		
7	GS	4.0	5.0	7.7	3.2	5.3	70.2	69.4	11.9	x		x		
8	GS	3.8	4.6	8.2	3.5	5.9	70.4	69.7	12.1	x		x		
9	GS	3.7	4.3	8.5	3.8	6.2	70.4	69.4	12.0	x		x		
10	GS	3.5	4.6	9.3	3.8	6.3	70.3	69.5	12.2	x		x		
11	GS	3.5	4.1	9.4	4.2	6.7	70.3	69.3	12.2	x		x		
12	GS	3.4	4.0	9.7	4.4	6.8	70.4	68.3	12.1	x		x		
13	GS	3.0	3.8	8.8	4.4	7.7	70.4	69.8	12.2	x		x		
14	---	---	---	3.0	---	---	---	---	9.8	x			x	Could not distinguish fill
15	GS	7.0	9.0	5.0	2.2	2.9	76.5	74.6	13.4	x			x	
16	GS	5.7	6.9	6.0	2.7	3.9	78.0	76.5	14.3	x			x	
17	GS	5.2	6.5	6.5	2.9	4.1	78.0	77.0	14.5	x			x	
18	GS	4.5	5.6	7.6	3.5	5.3	79.0	77.5	14.8	x			x	
19	GS	4.1	5.0	8.5	4.1	6.4	79.6	79.0	15.0	x			x	
20	GS	4.2	5.2	8.5	4.0	6.2	83.7	82.5	16.0	x			x	
21	BT	4.0	5.0	9.5	4.5	7.3	84.4	83.0	16.8	x			x	BT at 8.7 min
22	GS	4.5	5.6	9.0	4.3	6.8	83.0	82.2	16.4	x			x	
23	GS	3.5	4.5	10.5	4.5	7.5	75.8	75.4	14.0	x			x	
24	BT	3.4	4.0	9.5	5.0	8.5	76.0	75.5	14.3	x			x	BT at 5.0 min
25	GS	5.4	7.0	7.4	3.3	4.5	87.4	86.0	16.8	x			x	
26	BT	4.3	5.8	9.1	4.3	6.4	87.3	86.6	17.6	x			x	BT at 6.9 min
27	BT	5.8	7.3	8.0	4.0	5.3	90.2	88.0	18.0	x			x	BT at 8.5 min
28	GS	16.0	22.0	3.5	1.6	1.9	72.5	68.0	10.4	x			x	

SN4', 0.068 in. (Concluded)

Dates. From 1-24-66 through 2-7-66

Run No.	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
29	BT	3 0	3.5	7.9	6 6	7.1	75.5	75 5	13.9		x		x	
30	GS	3.5	3.6	6.9	5.9	6 2	76.0	75.8	13.8		x		x	
31	GS	3.0	3.4	7.2	3.5	5.9	71 3	71.3	12.2		x		x	
32	GS	4 5	5 5	6.6	4.6	4.9	85.0	85.5	16.5		x		x	
33	GS	3.0	3 4	8.0	6.0	6.5	76.5	76 5	14.0		x		x	
34	BT	3.5	4.0	8.0	6.2	6.6	86.3	85.7	17.0		x		x	
35	BT	3 2	3.3	8.8	7.1	7 5	77.5	77.5	14.3		x		x	
36	GS	13.5	18.5	3 6	1.4	1.9	74.5	71.0	11 5	x			x	Runs 36 - 46 horizontal plate orientation
37	---	---	---	4 5	---	---	---	---	13 3	x			x	
38	GS	7.4	10.2	5.5	2.4	3.1	84.0	81.1	15 0	x			x	
39	GS	4.7	6.3	8 5	3 8	6.0	84.3	83.5	16.0	x			x	
40	BT	3.8	4.8	9.5	4 5	7.5	80.5	78.8	15.0	x			x	
41	GS	4.3	5.2	8.4	4.1	6.5	81.0	80.0	15.0	x			x	
42	BT	4 3	4.8	9.7	4.7	7.4	74.5	74 0	13.0	x			x	
43	BT	4.2	4.8	8.8	4.4	7.0	59.6	60.5	11 4	x			x	
44	BT	4 9	5 5	8 4	4 3	5.8	83.6	83 2	15 2	x			x	
45	GS	5.2	6.2	7.2	4.0	5.5	79.5	78.5	14.0	x			x	
46	GS	4.7	5.2	8.0	4.3	6 7	71.8	71.5	11.8	x			x	Last of horizontal runs
47	GS	4 9	5.9	8.5	3 0	6 1	82.5	81 2	15.4	x			x	
48	GS	3 9	4.6	9.5	4.4	7.5	75 5	75.0	13.4	x			x	
49	GS	4.0	4.7	8 8	4.0	7.3	70.9	70.5	11.9	x			x	
50	GS	4.0	4.8	8.7	4.0	7.0	70.0	69.8	11 9	x			x	
51	GS	5.5	8.0	7.2	3.2	4.7	86.5	84.5	16.2	x			x	
52	GS	5.5	7.8	7.1	3.3	4.7	87.5	85.0	16.3	x			x	
53	GS	4 9	6.0	8.4	4.1	6 5	82.0	81.2	14.8	x			x	
54	GS	3.9	4.6	8.8	4.3	7.2	71.0	70.6	11.7	x			x	
55	GS	3.8	4.6	9.6	4.7	8.1	75.6	75.0	13 1	x			x	
56	GS	4.8	6.9	7.5	3.6	5.4	85.8	84.0	15.8	x			x	

SN4', 0.078 in.

Dates: From 2-9-66 through 2-10-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	2.0	2.5	7.1	5.8	6.6	64.5	64.0	9.7		x		x	
2	2.0	2.5	7.4	5.9	6.7	72.0	71.7	11.8		x		x	
3	2.0	2.5	8.0	6.6	7.4	76.5	76.3	12.9		x		x	BT at 2.8 min
4	2.7	2.9	6.8	5.5	6.2	76.0	75.8	13.2		x		x	
5	3.0	3.3	6.0	4.8	5.2	86.8	85.8	16.0		x		x	BT at 4.7 min
6	3.6	3.8	5.2	4.4	4.7	86.8	86.4	15.8		x		x	BT at 6.1 min
7	4.3	4.6	4.5	3.9	4.2	86.0	85.6	15.6		x		x	
8	5.5	6.0	4.8	3.9	4.4	86.6	86.1	15.4		x		x	
9	4.7	5.3	5.2	4.4	4.9	86.7	86.2	15.4		x		x	
10	5.4	5.7	5.5	5.2	5.3	86.0	85.5	15.1		x		x	BT at 6.3 min
11	4.3	4.9	8.4	2.9	6.0	82.8	81.9	15.0	x			x	BT at 5.3 min
12	4.8	6.3	7.3	2.6	4.9	82.8	81.2	14.5	x			x	
13	4.5	6.4	7.2	2.4	4.5	89.0	87.5	15.8	x			x	BT at 8.0 min
14	5.5	7.1	6.6	2.3	4.0	87.8	86.0	15.8	x			x	
15	11.0	14.0	3.6	1.3	2.1	76.9	74.6	11.5	x			x	
16	3.4	4.1	8.9	3.4	7.3	76.6	76.3	13.1	x			x	
17	3.1	3.6	9.8	3.8	8.6	70.2	70.0	11.4	x			x	
18	2.9	3.3	10.8	4.2	9.6	47.5	47.5	12.8	x			x	Incorrect Temperature

SN3

Dates: From 2-11-66 through 2-24-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	3.0	4.7	7.5	2.4	4.7	89.2	88.0	18.0	x		x		
2	6.5	8.5	3.5	1.2	1.6	81.2	79.7	12.0	x		x		
3	3.4	4.1	8.9	2.5	5.4	84.6	84.0	16.9	x		x		BT at 6.3 min
4	3.1	3.5	9.0	2.5	7.0	77.4	77.2	14.7	x		x		
5	2.5	3.5	9.7	2.5	8.0	71.0	71.0	12.8	x		x		
6	3.4	4.1	8.3	2.3	5.7	83.9	83.4	16.7	x		x		
7	3.1	3.6	9.5	2.7	7.5	77.7	77.5	15.0	x		x		
8	2.8	3.3	10.5	2.9	8.7	77.0	76.8	15.0	x		x		
9	2.8	3.2	11.2	3.1	9.6	77.8	77.2	14.8	x		x		
10	2.7	3.1	11.9	3.3	10.4	77.4	77.3	14.9	x		x		BT at 3.8 min
11	4.0	4.8	7.5	2.7	5.6	84.6	84.0	17.1	x		x		
12	3.7	4.5	8.5	3.0	6.1	84.0	83.5	17.2	x		x		
13	4.8	6.2	7.5	2.0	4.8	85.8	84.4	17.5	x		x		
14	3.0	3.5	10.0	2.7	7.6	80.2	80.0	15.7	x		x		BT at 4.8 min
15	3.4	4.3	7.5	2.3	5.5	76.5	76.3	14.2	x		x		
16	3.5	4.1	8.4	2.4	5.7	86.8	86.6	17.6	x		x		BT at 5.4 min
17	3.8	4.3	7.7	2.4	5.5	82.4	82.1	16.3	x		x		
18	3.2	3.8	8.8	2.7	6.6	81.0	80.6	15.8	x		x		

SN3´(Continued) Dates: From 2-11-66 through 2-24-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
19	3.3	3.8	8.5	2.7	6.5	81.5	81.2	15.9	x		x		
20	11.0	17.5	3.5	0.6	1.6	80.5	75.2	13.1	x			x	
21	3.3	3.9	7.5	0.7	5.6	72.4	72.1	12.8	x			x	
22	3.8	5.2	7.0	0.9	4.0	85.4	84.5	16.9	x			x	
23	3.2	4.2	8.2	0.9	5.8	81.6	81.0	15.6	x			x	
24	3.2	4.3	8.3	1.0	5.8	86.5	85.7	17.4	x			x	
25	2.4	3.4	9.5	0.9	7.4	80.9	80.5	15.3	x			x	
26	2.3	3.3	10.5	0.6	8.5	80.3	80.0	15.4	x			x	
27	2.2	3.1	11.5	0.7	9.0	80.6	80.6	15.4	x		x		BT at 3.1 min
28	2.8	3.0	6.5	5.1	5.4	87.0	87.0	16.9		x		x	BT at 3.5 min
29	2.5	2.9	6.5	5.3	5.7	85.6	85.5	15.4		x		x	BT at 2.9 min
30	2.3	2.5	7.5	5.8	6.1	75.5	75.2	12.8		x		x	BT at 2.8 min
31	2.8	3.3	6.0	4.9	5.1	80.0	79.6	14.5		x		x	BT at 3.6 min
32	2.5	3.9	5.1	3.5	4.1	80.0	79.5	14.4		x		x	
33	2.5	2.8	6.5	5.4	5.3	76.0	75.9	13.0		x		x	BT at 2.8 min
34	3.5	3.7	5.5	4.3	4.9	75.4	75.1	13.4		x		x	
35	---	---	4.3	3.0	---	84.0	---	---		x		x	No run - vapor lock
36	---	---	4.5	2.7	---	83.5	---	---		x		x	No run - vapor lock

SN3' (Continued)

Dates: From 2-11-66 through 2-24-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-4, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
37	---	---	4.5	2.4	---	84.0	---	---		x		x	No run - vapor lock
38	5.3	5.8	4.2	4.1	4.2	83.0	82.5	15.0		x		x	
39	4.8	6.2	4.3	3.9	4.3	85.5	84.5	15.5		x		x	
40	4.0	4.5	4.7	4.5	4.8	87.5	87.0	16.2		x		x	
41	6.0	8.1	4.3	1.5	2.2	79.6	78.6	13.0	x		x		
42	5.0	5.7	3.9	1.5	1.8	79.9	79.6	12.4	x		x		
43	3.0	3.8	10.8	2.9	3.8	80.6	81.0	14.6	x		x		BT at 3.1 min
44	3.0	3.5	---	2.5	3.2	81.5	81.3	11.3	x		x		
45	11.0	21.0	2.8	0.70	1.0	76.7	71.0	9.5	x		x		
46	4.2	4.8	8.3	2.3	3.9	83.2	82.2	3.4	x				BT at 5.3 min
47	3.7	4.4	8.6	2.3	4.8	77.2	76.8	13.5	x				BT at 4.5 min
48*	8.0	13.5	3.4	1.0	1.9	72.4	69.2	10.5	x				
49*	3.6	4.1	8.0	2.8	6.7	73.7	73.5	12.4	x				
50*	4.2	4.8	7.0	2.7	5.2	76.9	76.5	13.2	x				
51*	4.3	5.0	7.0	2.7	4.9	79.8	79.3	13.8	x				
52*	4.7	5.6	6.5	2.7	4.5	83.0	82.2	14.4	x				
53*	3.8	4.3	7.2	2.9	6.0	78.0	77.6	13.4	x				
54*	3.2	3.6	9.5	3.9	8.1	77.9	77.9	13.4	x				BT at 8.0 min

*Horizontal tests

SN3' (Concluded)

Dates: From 2-11-66 through 2-24-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
55*	5.9	6.8	5.5	2.3	3.7	85.5	84.4	14.8	x			x	
56*	5.3	6.2	6.0	2.6	3.9	87.0	86.0	15.1	x			x	
57*	3.8	4.6	8.0	3.3	5.9	80.5	79.8	13.7	x			x	BT at 5.5 min
58*	2.8	3.2	4.5	3.0	3.5	87.5	87.1	15.5		x		x	BT at 9.3 min
59*	2.5	3.7	4.4	2.8	3.4	86.7	86.0	14.9		x		x	BT at 5.3 min
60*	2.5	3.2	5.1	3.6	4.3	82.0	81.8	14.2		x		x	BT at 4.5 min
61*	2.2	2.7	6.0	4.4	5.3	78.2	77.7	13.3		x		x	BT at 6.2 min
62*	3.1	3.5	4.0	2.9	3.4	80.0	79.9	13.2		x		x	
63*	2.2	2.9	6.0	4.6	5.4	75.2	75.0	11.9		x		x	BT at 3.2 min
64*	2.5	3.2	5.0	4.0	4.6	74.4	74.2	11.8		x		x	BT at 5.2 min
65*	3.1	3.6	4.0	3.0	3.6	75.0	74.7	11.6		x		x	
66*	3.6	4.2	3.0	2.5	2.8	84.3	83.8	13.6		x		x	
67*	4.5	5.4	2.9	2.5	2.9	86.8	86.5	14.0		x		x	
68*	2.6	3.0	4.5	3.9	4.6	78.3	78.2	12.6		x		x	
69	5.2	7.2	5.2	1.6	3.1	79.4	78.0	12.5		x		x	
70	8.3	10.6	3.6	1.4	1.8	80.3	79.0	10.9	x		x		
71	2.7	3.3	10.6	7.0	9.1	78.4	78.0	13.8	x		x		BT at 4.7 min
72	3.0	3.3	9.4	2.4	7.8	72.7	72.5	11.7	x		x		
73	3.0	3.6	9.0	2.5	7.6	77.2	77.1	12.8	x		x		
74	3.7	4.3	6.9	2.1	4.9	88.4	87.9	15.0	x		x		

*Horizontal tests

SN10 (Rerun)

Dates: From 2-28-66 through 3-2-66

Run No.	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	GS	2.1	2.25	6.5	4.5	5.9	72.4	72.2	10.0		x		x	
2	GS	2.2	2.3	6.5	4.3	5.8	78.8	78.6	11.2		x		x	
3	GS	2.2	2.3	6.5	4.3	5.7	84.0	83.7	12.3		x		x	
4	GS	3.0	3.4	4.5	2.9	3.5	88.2	88.0	12.8		x		x	
5	BT	1.8	2.0	8.0	5.4	5.7	79.8	79.7	9.5		x		x	BT at 2.0 min
6	GS	1.8	2.0	7.1	4.8	6.5	74.0	74.0	10.2		x		x	
7	GS	1.8	1.9	8.0	5.4	7.3	75.0	75.0	10.7		x		x	
8	BT	1.7	1.8	9.0	6.2	6.25	75.5	75.4	9.7		x		x	BT at 1.8 min
9	GS	2.2	2.3	6.6	4.1	5.5	72.0	72.0	9.7		x		x	
10	GS	3.0	3.3	5.0	2.9	3.7	89.2	89.2	13.0		x		x	
11	GS	2.6	2.9	5.6	3.2	4.3	89.5	89.4	13.0		x		x	
12	GS	2.4	2.8	6.3	3.7	5.0	89.5	89.4	13.3		x		x	
13	GS	2.2	2.3	7.1	4.1	5.6	89.2	89.0	13.3		x		x	
14	BT	2.0	2.2	7.8	4.9	5.4	89.5	89.5	8.6		x		x	BT at 2.2 min
15	BT	2.1	2.25	7.5	5.0	6.7	84.8	84.5	12.6		x		x	BT at 3.7 min
16	BT	1.9	2.1	8.4	5.7	8.0	79.1	79.0	10.6		x		x	BT at 2.4 min
17	GS	2.4	2.6	5.9	4.0	5.4	70.8	70.8	9.2		x		x	

SN5

Dates: From 3-14-66 through 3-17-66

Run No.	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	GS	3.9	5.2	6.5	2.6	4.0	81.6	81.0	15.6	x				
2	GS	2.8	3.25	10.0	3.7	7.9	72.4	72.4	12.8	x				
3	GS	3.6	4.8	7.5	2.8	5.0	80.0	79.1	15.4	x				
4	GS	4.0	5.5	7.2	3.0	4.6	83.0	82.0	16.4	x				
5	GS	3.5	7.3	6.5	2.3	3.8	86.5	84.2	16.8	x				
6	GS	3.8	6.0	7.2	2.7	4.5	86.6	85.0	17.4	x				
7	GS	3.5	4.8	8.0	3.2	5.2	87.0	86.5	17.4	x				
8	BT	3.1	4.0	9.1	3.5	6.0	86.5	86.1	17.5	x				BT at 4.6 min
9	GS	3.25	3.8	9.5	3.6	6.9	82.0	81.8	15.9	x				
10	BT	2.85	3.5	10.2	3.75	7.1	82.7	82.5	16.1	x				BT at 3.5 min
11	GS	2.8	3.25	10.5	3.9	7.8	78.8	78.6	14.9	x				
12	BT	2.7	3.5	11.0	4.1	6.0	79.5	79.4	14.9	x				BT at 3.5 min
13	BT	2.7	3.3	11.0	4.3	7.1	77.0	77.0	14.2	x				BT at 3.3 min
14	GS	11.6	12.5	3.5	1.3	1.8	76.5	76.0	11.6	x				
15	GS	2.8	3.3	10.5	3.7	8.4	76.2	76.0	14.0	x				
16	GS	2.6	3.0	11.1	4.3	9.3	77.0	77.0	14.4	x				
17	GS	2.5	2.9	12.0	4.6	10.0	76.6	76.5	14.1	x				
18	GS	2.5	3.25	11.1	4.2	9.0	80.0	79.8	15.1	x				

SN5′ (Concluded)

Dates: From 3-14-66 through 3-17-66

Run No.	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
19	BT	2.7	3.3	11.1	4.2	8.4	80.8	80.5	15.4	x				BT at 3.3 min
20	GS	3.0	4.3	5.0	3.3	3.9	84.0	84.0	15.9		x			
21	BT	2.8	3.4	6.0	4.3	4.8	84.5	84.1	16.0		x			BT at 3.7 min
22	BT	2.8	3.5	6.0	4.2	4.9	79.7	79.5	14.7		x			
23	GS	2.75	3.0	6.0	4.4	5.3	76.4	76.4	13.5		x			
24	BT	2.4	3.0	7.0	5.1	5.8	76.5	76.4	13.4		x			BT at 3.0 min
25	GS	2.0	2.5	7.0	5.8	6.9	71.1	71.1	11.9		x			
26	GS	2.25	2.5	7.5	5.7	6.8	70.8	70.8	11.8		x			
27	GS	2.1	2.4	8.1	6.2	7.4	70.5	70.5	11.6		x			
28	GS	3.0	3.5	5.3	3.8	4.4	80.0	79.9	14.3		x			
29	GS	1.8	2.3	8.5	6.5	8.1	71.7	71.7	12.2		x			
30	GS	1.8	2.25	9.1	7.2	8.7	70.7	70.7	11.8		x			
31	GS	1.9	2.2	9.8	7.6	9.2	70.6	70.6	11.8		x			
32	BT	1.75	2.0	10.4	8.3	9.1	71.6	71.6	11.1		x			BT at 2.0 min
33	GS	2.75	3.0	6.0	4.5	5.3	70.5	70.5	11.3		x			
34	GS	8.0	11.7	14.3	1.5	1.8	80.0	78.0	12.3		x	x		Profile
35	GS	2.75	3.5	10.0	3.8	7.9	80.0	79.8	14.5			x		Bypassing orifice reg

SN7'

Dates: From 3-21-66 through 3-24-66

Run No.	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	GS	3.3	4.8	6.0	2.0	3.5	81.8	81.8	14.4	x				
2	GS	3.3	4.5	6.0	2.1	3.3	86.2	86.0	16.1	x				
3	BT	3.0	4.5	7.0	2.4	4.3	86.6	86.2	17.1	x				BT at 9.7 min
4	GS	3.2	4.0	7.0	2.7	4.9	78.5	78.0	14.9	x				
5	GS	3.6	4.1	6.0	2.3	4.1	69.6	69.6	11.9	x				
6	GS	2.4	3.4	8.0	2.8	6.3	77.0	77.0	14.8	x				
7	BT	2.7	3.4	9.0	3.3	6.2	78.2	78.2	15.1	x				BT at 3.4 min
8	GS	2.5	3.2	9.0	3.5	7.7	71.5	71.5	13.1	x				
9	BT	2.4	3.0	9.9	3.7	5.6	72.0	72.0	12.6	x				BT at 3.0 min
10	GS	3.4	4.2	6.4	3.3	4.3	82.4	82.4	15.7	x				
11	BT	3.1	4.1	7.4	3.3	5.7	81.8	81.6	15.8	x				
12	GS	6.3	7.0	3.9	1.9	2.5	80.8	80.5	12.8	x				
13	GS	6.5	8.5	16.0*	1.3	2.2	80.0	79.9	12.0	x		x		Profile
14	GS	2.5	3.2	9.2	3.3	8.4	73.3	73.2	13.4	x		x		Bypassing orifice reg
15	GS	2.1	2.2	7.3	6.5	6.9	70.4	70.4	12.8		x			
16	GS	2.9	3.1	4.1	3.0	3.3	85.2	85.2	15.8		x			
17	GS	2.6	2.8	5.0	4.0	4.3	81.2	81.2	15.3		x			
18	BT	2.2	2.6	6.0	5.1	5.2	81.5	81.5	15.3		x			BT at 2.6 min
19	BT	2.2	2.3	6.0	5.1	5.2	75.0	75.0	13.0		x			BT at 3.0 min
20	GS	2.1	2.5	6.0	5.1	5.5	72.6	72.6	12.8		x			
21	BT	2.1	2.4	6.4	5.5	6.0	73.0	73.0	12.8		x			BT at 5.3 min
22	GS	2.7	3.0	4.6	3.9	4.2	77.5	77.5	14.0		x			
23	GS	2.8	3.3	4.2	3.4	3.7	84.3	84.3	15.6		x			
24	BT	2.6	3.0	4.6	4.0	4.3	85.0	85.0	16.1		x			BT at 5.7 min
25	GS	8.0	9.5	16.1*	1.2	1.8	80.4	80.2	12.4	x		x		Profile

*Orifice regulator supply pressure

SN9

Dates: From 3-23-66 through 4-8-66

Run No	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	GS	15.0	19.0	16.0*	1.1	1.6	73.8	70.0	12.3	x		x		Profile
2	---	---	---	4.0	---	---	---	---	12.0	x			x	Could not distinguish fill
3	GS	9.7	12.0	5.1	1.8	2.8	74.0	72.0	13.0	x			x	
4	GS	7.1	8.6	6.1	2.1	3.9	76.0	75.0	13.9	x			x	
5	GS	5.7	5.8	7.2	2.5	5.1	77.9	76.6	14.3	x			x	
6	GS	4.8	5.8	8.0	2.8	5.8	78.1	77.4	14.3	x			x	
7	BT	4.2	4.9	9.0	3.1	6.6	78.5	77.6	14.5	x			x	BT at 4.9 min
8	GS	4.5	4.9	8.5	3.4	7.5	73.8	73.5	13.1	x			x	
9	GS	4.0	4.5	9.4	3.7	8.4	74.4	74.0	13.0	x			x	
10	GS	3.5	4.0	10.5	4.0	9.0	73.5	73.2	12.5	x			x	
11	BT	3.4	3.8	11.5	4.3	10.3	73.2	72.7	12.6	x			x	BT at 4.4 min
12	GS	5.0	5.5	7.4	2.5	3.4	69.0	68.8	11.4	x			x	Run out of water at comp of fill
13	GS	5.0	5.7	7.4	2.8	6.0	66.0	65.7	10.7	x			x	
14	GS	6.5	7.0	7.4	2.9	5.5	81.2	80.6	15.4	x			x	
15	GS	5.5	6.1	7.9	3.0	5.5	80.0	79.6	14.6	x			x	
16	BT	4.8	5.7	8.9	3.2	7.0	80.5	79.0	14.5	x			x	BT at 6.5 min
17	GS	13.5	15.6	5.1	2.2	3.2	78.7	76.8	15.4	x			x	
18	GS	8.6	10.2	6.5	2.7	4.2	83.7	82.0	16.2	x			x	
19	GS	6.7	8.0	7.2	2.9	5.4	84.2	82.6	16.3	x			x	
20	GS	5.5	7.0	8.1	3.2	6.0	86.5	85.0	16.5	x			x	
21	BT	5.1	5.8	9.0	3.4	6.4	86.8	86.0	11.6	x			x	BT at 5.8 min
22	GS	3.5	4.0	6.9	5.8	6.2	70.4	70.4	11.6		x		x	

*Orifice regulator supply pressure

SN9′ (Concluded)

Dates: From 3-23-66 through 4-8-66

Run No	Results	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
										Flowmeter		Orifice Reg		
		Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
23	BT	2.4	2.5	7.6	6.3	6.8	73.5	73.5	12.5	x	x		x	BT at 3.1 min
24		-	---	4.1	---	---	---	---	13.8		x		x	Could not distinguish fill
25	GS	1.4	3.8	5.0	4.0	4.4	78.3	78.1	13.7		x		x	
26	GS	3.0	3.1	5.6	4.5	4.8	74.2	74.2	12.0		x		x	
27	BT	2.9	3.0	6.0	5.1	5.6	78.8	78.6	12.9	x	x		x	BT at 3.4 min
28	BT	2.5	3.5	4.6	3.7	4.2	83.8	83.6	14.5		x		x	BT at 4.5 min
29	BT	3.5	4.0	4.0	3.0	3.5	82.0	82.0	14.8		x		x	BT at 5.8 min
30	GS	2.3	2.4	8.0	6.7	7.2	69.1	69.0	10.7		x		x	
31	BT	2.2	2.25	9.0	7.7	8.15	72.1	72.1	11.4		x		x	BT at 2.5 min
32	---	---	---	3.6	---	---	---	---	15.3		x		x	Could not distinguish fill
33	GS	4.4	5.2	4.1	3.0	3.2	82.5	81.5	14.7		x		x	
34	GS	2.5	2.6	7.8	6.7	7.1	71.5	71.3	13.0		x		x	
35	GS	4.0	4.1	4.0	3.3	3.8	74.8	74.7	12.3		x		x	
36	GS	9.0	11.0	8.6	1.3	2.0	77.6	75.2	13.0	x		x		Profile
37	GS	---	---	3.6	1.5	1.5	---	76.5	11.5	x		x		Profile (with first stage reg)
38	GS	---	---	4.7	1.4	1.4	---	74.8	11.7	x		x		Profile (with first stage reg)
39	GS	14.0	16.5	4.6	1.3	2.2	65.0	63.0	10.0	x		x		Profile (with first stage reg)
40	GS	9.5	11.5	4.6	1.3	2.9	58.5	57.5	7.7	x		x		Profile (with first stage reg)
41	GS	20.8	22.7	5.4	1.5	3.4	70.5	69.2	11.7	x		x		Profile (with first stage reg)
42	GS	22.8	25.2	3.0	1.3	2.5	68.5	67.0	11.4	x		x		Profile (with first stage reg)
43	GS	16.5	20.5	4.3	1.6	3.2	71.6	68.0	12.0	x		x		Profile (with first stage reg)
44	GS	12.5	16.5	5.6	1.3	3.0	72.3	70.6	12.2	x		x		Profile (with first stage reg)

SN6′

Dates: From 6-10-66 through 6-16-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	3.7	4.6	4.0	1.6	3.4	82.5	82.5	13.3	x			x	
2	3.5	4.7	4.0	1.7	3.2	87.5	87.5	15.4	x			x	
3	3.5	4.7	6.2	2.8	4.8	76.7	76.5	14.1	x			x	
4	3.4	4.2	7.0	2.8	5.4	75.0	75.0	13.8	x			x	
5	3.4	4.4	6.9	2.8	4.8	82.5	82.5	15.8	x			x	BT at 5.5 min
6	3.2	3.9	7.6	3.0	5.9	76.0	76.0	14.4	x			x	
7	3.0	3.6	8.4	3.2	6.8	76.1	76.1	14.4	x			x	
8	3.0	3.6	8.3	3.2	6.6	78.7	78.7	15.0	x			x	BT at 5.2 min
9	3.3	4.2	6.9	2.8	5.0	81.5	81.5	15.6	x			x	
10	4.4	5.2	4.4	2.0	2.9	88.5	88.5	14.5	x			x	
11	4.0	4.9	5.0	2.1	3.2	88.0	88.0	16.5	x			x	
12	3.7	4.5	5.0	2.2	3.3	88.0	88.0	16.9	x			x	
13	3.6	4.7	5.5	2.2	3.7	88.0	88.0	16.4	x			x	
14	4.2	5.0	5.1	2.2	4.2	66.8	66.8	10.9	x			x	
15	3.7	5.2	5.2	2.0	3.3	88.0	88.0	16.6	x			x	
16	3.1	4.7	5.9	2.2	3.8	89.5	89.5	17.6	x			x	
17	3.1	3.9	7.4	2.8	5.7	82.6	82.6	16.5	x			x	

SN6 (Concluded)

Dates: From 6-10-66 through 6-16-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp. T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
18	3.0	3.7	8.2	2.8	6.3	82.0	82.0	16.4	x			x	BT at 3.9 min
19	3.6	4.7	5.8	2.2	3.7	87.6	87.6	16.0	x			x	
20	3.3	4.4	6.8	2.5	4.7	87.6	87.6	17.2	x			x	
21	4.5	5.8	4.2	1.6	2.9	80.6	80.5	14.1	x		x		
22	2.6	3.3	9.1	3.2	7.9	77.2	77.2	14.6	x		x		Bypassing orifice reg
23	2.7	3.4	9.4	3.5	7.6	77.5	77.5	14.5	x		x		Bypassing orifice reg BT at 3.7 min
24	2.2	2.3	7.0	6.0	6.8	79.3	79.3	15.0		x		x	
25	2.0	2.1	7.0	6.0	6.8	70.0	70.0	12.0		x		x	
26	2.6	2.8	5.1	4.2	4.6	86.2	86.0	16.8		x		x	BT at 3.1 min
27	2.2	2.4	6.4	5.4	6.1	81.0	81.0	15.6		x		x	
28	2.6	3.0	4.4	3.6	4.0	84.8	84.8	16.0		x		x	
29	1.9	2.1	8.0	7.1	7.4	78.5	78.5	13.8		x		x	BT at 2.4 min
30	1.9	2.2	8.0	7.1	7.8	73.2	73.2	12.6		x		x	BT at 2.3 min
31	1.8	1.9	8.3	7.6	8.6	69.5	69.5	11.8		x		x	
32	1.9	2.1	7.6	6.8	7.6	75.5	75.5	13.5		x		x	
33	1.8	1.9	9.0	8.0	8.7	72.5	72.5	12.1		x		x	BT at 2.2 min
34	2.2	2.3	5.9	5.2	5.9	70.5	70.5	11.9		x		x	

SN11'

Dates: From 6-20-66 through 6-23-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	3.5	4.3	7.0	2.5	5.4	73.0	73.0	14.1	x			x	
2	3.5	5.5	5.0	1.8	3.0	77.5	77.5	15.1	x			x	
3	3.5	4.5	6.0	2.0	4.0	74.8	74.8	14.4	x			x	
4	3.2	4.0	6.0	2.0	4.9	76.3	76.3	14.5	x			x	
5	3.1	3.7	7.8	2.4	6.0	74.6	74.6	14.4	x			x	
6	2.9	3.5	8.3	2.4	6.2	76.0	76.0	14.7	x			x	
7	2.7	3.3	9.4	3.2	8.0	75.2	75.2	14.8	x			x	BT at 8.1 min
8	3.4	5.0	5.8	2.8	3.8	83.7	83.6	16.7	x			x	
9	3.1	4.3	6.4	2.1	4.3	84.5	84.5	17.1	x			x	
10	2.9	4.1	7.1	2.3	5.1	84.5	84.5	17.2	x			x	
11	2.7	3.7	7.8	2.5	5.8	83.2	83.2	17.0	x			x	
12	2.4	3.6	8.6	2.7	6.2	84.6	84.5	17.6	x			x	
13	2.4	4.0	8.5	2.8	6.0	85.6	85.6	17.9	x			x	
14	2.4	3.8	9.0	2.6	6.0	85.6	85.4	17.8	x			x	
15	2.3	3.6	9.6	2.6	6.6	86.4	86.4	18.0	x			x	

SN11′(Concluded)

Dates: From 6-20-66 through 6-23-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
16	2.2	3.5	10.0	2.8	6.6	87.0	87.3	18.0	x			x	
17	2.5	3.8	8.1	2.6	6.2	77.0	76.5	15.0	x			x	
18	2.4	3.6	9.0	3.0	7.0	78.4	78.4	15.5	x			x	
19	2.3	3.2	10.0	3.1	8.2	76.2	76.2	15.0	x			x	
20	2.2	3.1	10.6	3.0	8.2	77.5	77.5	14.9	x			x	
21	2.2	2.8	11.4	3.3	9.5	74.6	74.6	13.5	x			x	
22	2.1	2.7	12.2	3.6	10.7	74.8	74.6	14.6	x			x	
23	2.2	3.3	10.6	3.4	8.4	84.6	84.4	17.7	x			x	
24	2.2	3.3	11.2	3.3	8.8	84.5	84.5	17.5	x			x	BT at 3.9 min
25	2.3	3.3	10.0	3.1	7.8	80.6	80.6	16.0	x			x	
26	2.2	2.9	11.6	3.2	9.0	79.6	79.6	15.8	x			x	
27	2.1	2.8	12.2	3.8	8.5	80.4	80.4	15.8	x			x	BT at 2.8 min
28	5.7	7.5	4.4	2.0	2.6	79.9	79.5	13.8	x		x		
29	3.6	4.3	7.0	2.5	4.4	69.7	69.7	11.5	x		x		Bypassing Orifice Reg

SN13

Dates: From 6-24-66 through 6-25-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	M/W Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	3.0	3.9	7.0	2.4	5.4	69.3	69.2	13.4	x			x	
2	2.9	3.4	8.0	2.6	6.2	70.5	70.5	13.9	x			x	
3	2.1	2.6	9.4	3.0	7.8	69.5	69.5	13.4	x			x	BT at 4.8 min
4	3.6	4.2	4.5	1.3	1.7	84.5	84.5	17.5	x			x	
5	3.4	6.7	5.2	1.7	2.6	85.5	84.0	18.0	x			x	
6	3.0	6.0	6.0	2.2	2.3	84.5	83.2	18.0	x			x	Hard to distinguish fill
7	3.1	6.0	5.8	1.9	3.3	85.4	83.6	18.0	x			x	
8	2.9	4.5	6.6	2.1	4.0	84.5	84.0	18.0	x			x	
9	2.6	4.0	7.2	2.4	4.6	84.5	84.0	18.0	x			x	BT at 4.2 min
10	3.2	4.6	5.9	2.0	4.0	78.8	78.4	15.7	x			x	
11	2.8	3.7	7.1	2.4	4.5	77.0	76.9	15.7	x			x	BT at 4.0 min
12	2.9	3.8	6.8	2.5	5.6	73.0	72.8	14.2	x			x	BT at 4.0 min
13	3.5	6.5	4.2	1.6	2.4	79.7	79.5	15.6	x		x		
14	3.2	4.8	5.6	1.6	3.4	75.5	75.0	14.9	x		x		Bypassing orifice reg

SN 10

Dates: From 6-27-66 through 6-30-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	3.3	4.6	6.0	1.8	4.0	78.9	78.4	15.2	x			x	
2	2.7	3.4	8.0	2.5	6.2	71.1	71.1	12.8	x			x	
3	3.6	5.5	4.6	1.3	2.3	83.4	82.6	15.9	x			x	
4	3.2	5.1	5.6	1.6	3.1	83.5	82.4	16.0	x			x	
5	2.9	4.5	6.5	1.8	3.8	84.3	83.9	16.6	x			x	
6	2.8	4.3	6.9	1.9	4.2	85.5	84.9	17.0	x			x	
7	2.8	4.2	7.2	2.2	5.2	77.4	77.2	14.2	x			x	
8	2.8	4.4	6.9	2.0	4.4	85.5	85.0	16.8	x			x	
9	2.6	3.9	8.0	2.2	5.3	85.0	84.3	16.7	x			x	
10	2.5	3.7	9.0	2.5	6.1	84.5	84.0	17.0	x			x	
11	2.5	3.4	9.9	2.8	7.1	84.6	84.3	16.9	x			x	
12	2.6	3.2	10.0	2.8	7.6	77.2	77.0	14.7	x			x	BT at 3.5 min
13	2.6	3.2	9.4	2.8	7.6	74.4	74.2	13.9	x			x	
14	2.7	3.6	9.0	2.6	6.5	85.0	84.7	16.4	x			x	
15	2.5	3.4	10.2	3.0	7.5	84.5	84.3	16.7	x			x	
16	2.4	3.1	11.0	3.2	8.2	85.0	84.7	16.8	x			x	
17	2.2	2.9	11.9	3.5	7.8	85.5	85.4	16.7	x			x	BT at 3.0 min
18	2.6	3.3	9.6	2.8	7.7	74.8	74.8	13.4	x			x	
19	2.3	2.7	12.0	3.6	10.4	70.5	70.5	12.1	x			x	
20	2.6	3.4	9.2	2.6	7.0	79.2	79.2	14.5	x			x	
21	4.3	6.5	4.2	1.5	2.6	79.8	79.6	12.7	x		x		

SN12′

Dates: From 7-14-66 through 7-15-66

Run No.	Fill Time, min		Bladder Pressure, P-4, psia	Water Inlet Pressure, P-1, psia		M/W Inlet Temp, T-2, °F		Maximum Cooling Capacity, kw	System Configuration				Remarks
									Flowmeter		Orifice Reg		
	Start	Comp		Start	Comp	Start	Comp		With	W/O	With	W/O	
1	2.9	4.1	7.3	2.2	5.0	75.0	75.0	13.0	x			x	
2	2.7	3.4	8.5	2.8	7.0	69.8	69.0	11.5	x			x	
3	2.5	3.1	9.4	2.5	7.4	70.0	70.0	11.4	x			x	
4	2.4	3.0	10.3	2.9	8.4	68.5	68.5	11.4	x			x	
5	2.3	2.9	11.8	3.2	9.4	70.5	70.5	12.0	x			x	BT at 3.1 min
6	3.3	5.3	5.9	1.7	3.0	84.5	82.0	15.8	x			x	
7	2.8	4.4	7.7	2.2	4.4	86.5	85.0	16.2	x			x	
8	2.6	3.8	8.8	2.6	5.4	86.5	85.0	16.5	x			x	BT at 4.7 min
9	2.5	3.4	9.5	2.7	6.7	80.5	80.0	14.7	x			x	BT at 4.7 min
10	2.8	3.5	8.2	2.6	6.3	74.5	74.0	12.4	x			x	
11	2.7	3.5	8.2	2.7	6.4	75.0	75.0	13.0	x			x	
12	2.9	4.0	7.4	2.2	5.2	78.0	77.5	13.5	x			x	
13	9.2	11.6	4.4	2.1	2.8	73.0	68.5	12.4	x		x		

APPENDIX III
ANALYSIS OF INSTRUMENTATION ERROR

1. Estimated instrumentation accuracies:

Pressure measurements	±0.2 psi
M/W inlet and outlet temperature measurements (thermistors)	±0.1°F
Water inlet temperature (thermocouple) . .	0.5°F
Water flow rate (scales)	±0.5 lb_m/hr
M/W flow rate (turbine flowmeter)	±0.5 percent

2. Estimated maximum heat-transfer calculation errors:

a. M/W side

Temperature error	±0.2°F (inlet and outlet)
Flow rate error	±0.5 percent

Therefore, maximum error on the M/W side is,

$$Q_{e1} = \dot{M}_1 \pm (0.005)\ (\dot{M}_1)\ C_p\ (T_1 - T_2) \pm 0.2$$

$$-\dot{M}_1 C_p (T_1 - T_2) \qquad (1)$$

where:

Q_{e1} = Possible heat-transfer calculation error on the M/W side, Btu/hr

$\dot{M}_1$ = M/W flow rate, lb_m/hr

T_1 = M/W inlet temperature, °F

T_2 = M/W outlet temperature, °F

C_p = M/W specific heat, Btu/lb_m-°F

Note:

$$C_p = 0.688 + (2.65 \times 10^{-3})\ [(T_1 + T_2)/2] - (12.4 \times 10^{-6})\ [(T_1 + T_2)/2]^2$$

b. Water side

Water flow rate error	±0.5 lb_m/hr

Assuming a Δh of 1032 Btu/lb_m, a possible error of ±10.0 Btu/lb_m is estimated.

Therefore, maximum error on the water side is,

$$Q_{e2} = (\dot{M}_2 \pm 0.5)\ (1032 \pm 10.0) - \dot{M}_2\ (1032) \tag{2}$$

Where:

Q_{e2} = Possible heat-transfer calculation error on the water side, Btu/hr

$\dot{M}_2$ = Water flow rate, lb_m/hr

3. Example: Assume the following test data has been recorded.

$\dot{M}_1 = 8000\ lb_m/hr$

$T_1 = 63.8°F$

$T_2 = 59.0°F$

$\dot{M}_2 = 29.8\ lb_m/hr$

Therefore

$C_p = 0.804\ Btu/lb_m{-}°F$

$Q_1 = (8000)\ (0.804)\ (4.8) = 30{,}800\ Btu/hr$

$Q_2 = (29.8)\ (1032) = 30{,}800\ Btu/hr$

But from Eq. (1),

$$Q_{e1} = [8000 \pm (0.005)\ (8000)]\ [(0.804)\ (4.8 \pm 0.2)] - 30{,}800$$

$= +1520$ Btu/hr for positive case or -1361 Btu/hr for negative case,

and from Eq. (2),

$$Q_{e2} = (29.8 \pm 0.5)\ (1032 \pm 10.0) - 30.800$$

$= +773$ Btu/hr for positive case or -855 Btu/hr for negative case.

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13 ABSTRACT

Twelve refrigeration units (sublimators) were subjected to simulated flight environments and evaluated as to their critical starting characteristics and heat-transfer capacity under nominal operating conditions. The sublimator is used to cool various instrument components aboard the Saturn S4B stage of the Saturn IB and Saturn V vehicles. It is a two-component system using pure water (which is sublimated through porous sintered nickel plates) as the coolant and a methanol/water (M/W) solution (which comes into thermal contact with the plates) as the heat-transfer fluid to cool the instrument packages. Various M/W inlet temperatures (heat load), and water inlet pressures, were imposed on each sublimator, and its critical starting limitations were defined. Heat-transfer capacity was determined by conventional calorimeter methods for each set of conditions. Starting characteristics for each sublimator were adequate and satisfactory. All sublimators except one performed at or above the rated 9-kw cooling capacity at nominal conditions. In addition to the 12 units evaluated under simulated flight conditions, one unit was subjected to certain developmental tests for the purpose of determining the effect of low heat load on the sublimator.

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